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Geophysical Investigations of the Western Ohio-Indiana Region

ORIGINAL

Final Report
October 1981 - September 1986

Prepared by D. H. Christensen, H. N. Pollack, T. Lay, S. Y. Schwartz

Department of Geological Sciences
The University of Michigan

Prepared for
U.S. Nuclear Regulatory
Commission

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Previous Reports

Four major reports concerning this investigation were published under the previous contract NRC 04-76-192:

Mauk, F.J., D. Coupland, D. Christensen, J. Kimball, P. Ford, 1979, Geophysical Investigations of the Anna, Ohio, Earthquake Zone: Annual Progress Report for the U. S. Nuclear Regulatory Commission, July 1978-July 1979, NUREG/CR-1065.

Mauk, F.J., S.G. Henry, D.H. Christensen, J. Sauber, C. Lanford, W. Meerschaert, J.K. Kimball, 1980, Geophysical Investigations of the Anna, Ohio, Earthquake Zone: Annual Progress Report for the U. S. Nuclear Regulatory Commission, July 1979-1980, NUREG/CR-1649.

Mauk, F.J., D.H. Christensen, 1980, A Probabilistic Evaluation of Earthquake Detection and Location Capability for Illinois, Indiana, Kentucky, Ohio and West Virginia: Report for the U. S. Nuclear Regulatory Commission, September 1980, NUREG/CR-1648.

Jackson, P.L., D.H. Christensen, F.J. Mauk, 1982, Geophysical Investigations of the Western Ohio - Indiana Region: Final Report for the U. S. Nuclear Regulatory Commission, November 1975-September 1981, NUREG/CR-2484.

Annual reports under contract NRC-04-81-195-04:

Christensen, D.H., M.G. Wiedenbeck, P.L. Jackson, 1983, Geophysical Investigations of the Western Ohio - Indiana Region: Annual Report for the U. S. Nuclear Regulatory Commission, October 1981-September 1982, NUREG/CR-3145, Vol. 1.

Pollack, H.N., D.H. Christensen, 1984, Geophysical Investigations of the Western Ohio - Indiana Region: Annual Report for the U. S. Nuclear Regulatory Commission, October 1982-September 1983, NUREG/CR-3145, Vol. 2.

Pollack, H.N., D.H. Christensen, 1985, Geophysical Investigations of the Western Ohio - Indiana Region: Annual Report for the U. S. Nuclear Regulatory Commission, October 1983 - September 1984, NUREG/CR-3145, Vol. 3.

Pollack, H.N., D.H. Christensen, J. Welc, 1986, Geophysical Investigations of the Western Ohio - Indiana Region: Annual Report for the U. S. Nuclear Regulatory Commission, October 1984-September 1985, NUREG/CR-3145, Vol. 4.

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Abstract

Earthquake activity in the Western Ohio - Indiana region has been monitored with a precision seismograph network consisting of nine stations located in west-central Ohio and four stations located in Indiana. Five local and near-regional earthquakes have been recorded and located during the 1985-86 fiscal report period, ranging in magnitude from 0.5 to 5.0m_b. The two largest of these events (January 31, 1986 near Cleveland, Ohio, magnitude = 5.0m_b, and July 12, 1986 near St. Marys, Ohio, magnitude = 4.5m_b) were felt with minor damage reported in each case. Focal mechanisms and isoseismal maps for these events are included in this report. These events are the largest to have occurred in Ohio since the events of March 2 and March 9, 1937 (magnitude = 4.5 and 4.9, respectively). The remaining three earthquakes of this report period all occurred in Ohio, north of the array. A total of 42 local and near-regional events, eleven of which have been felt, have now been recorded by the Ohio-Indiana array since its initiation in 1976. Teleseismic P-wave arrival and residual tables have been updated to include newly acquired data. The results are similar to those in previous years. The local velocity structure has been investigated using data acquired during a refraction experiment in the summer of 1984 and travel time data of local and near regional earthquakes.

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Summary

During the period from October, 1985 through September, 1986 the Western Ohio-Indiana network has been operational an average of 82% of the time. Over the complete five year period of the current contract the stations have been operational 87% of the time. Changes in the array include the replacement of the Mark Products L-4C geophones and Interproducts VCO/Amplifier packages in the Ohio stations with Teledyne Geotech S-500 geophones and 42.50-1 and 46.22 VCO/Amplifier systems and replacement of the rechargeable batteries.

Five local and near regional earthquakes have been recorded during the fiscal year. These events ranged in magnitude from 0.5 to 5.0m_b. The two largest of these events (January 31, 1986 near Cleveland, Ohio, magnitude = 5.0m_b, and July 12, 1986 near St. Marys, Ohio, magnitude = 4.5m_b) were felt with minor damage reported in each case. The focal mechanisms for both of the 1986 events are very similar and represent strike-slip motions on NW-SE or SW-NE nodal planes with horizontal compressional stress axes oriented E-W. Isoseismal maps from Carl Stover of the USGS are included in this report. These events are the largest to have occurred in Ohio since the events of March 2 and March 9, 1937 (magnitude = 4.5 and 4.9, respectively). The remaining three earthquakes of this report period all occurred in Ohio, north of the array.

A total of 42 local and near regional events, eleven of which have been felt, have now been recorded by the Ohio-Indiana array since its initiation in 1976. The occurrence of the St. Marys event of 1986 suggests that the proposed Anna-Champaign fault is the source of the larger events in the Anna area.

The teleseismic P-wave arrival and residual tables have been updated to include newly acquired data. The results from this ongoing study agree with those from previous years but are included for completeness.

Travel time data from local and regional earthquakes are interpreted to obtain a local velocity structure. The data are consistent with a simple one or perhaps two layer structure overlying the Moho in the Anna region. Results from a joint seismic refraction study with the University of Kentucky and Memphis State University are also included. The travel time data from both the local and regional earthquakes and the refraction survey indicate that the P-wave arrivals which are the first arrivals at distances less than 200 km travel at an apparent velocity of 6.36 km/sec. A slightly faster and more complicated branch of secondary P-wave arrivals (P^*) were also found with a velocity between 6.63 to 6.76 km/sec. P_n and S_n arrivals at distances greater than 200 km travel at apparent velocities of about 8.12 and 4.58 km/sec, respectively. An apparent velocity of about 3.61 km/sec was also interpreted for the S_g (or L_g) arrival times.

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PREFACE

This is the final report under the five year contract NRC-04-81-195-04, a continuation of the effort funded under contract NRC-04-76-192: The contract includes maintenance and systematic processing of a 9-station seismic array in western Ohio initiated in 1976, and the subsequent expansion in 1981 to include a 4-station array in Indiana, in addition to concurrent regional investigations. Portions of this report have been taken directly from earlier reports for completeness. We wish to express our appreciation to Scott Baird for keeping a wide range of instruments and computer peripherals in constant working condition, and to Judi Sheridan, Tim Sheridan, Joan Welc and Susan Carter for their help in successfully operating the seismic network. We would also like to thank Marvin Speece for his dedication in performing the refraction survey in the summer of 1984, and Carl Stover from the USGS for providing us with isoseismal maps of the Perry and St. Marys earthquakes.

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I
GEOLOGY AND BASEMENT STRUCTURE OF THE ANNA REGION

Geology

The majority of Ohio, Indiana, and Michigan, including the Anna Seismic Region is underlain by a well developed basin and arch structural framework. The Indiana-Ohio Platform in western Ohio and eastern Indiana is a broad, positive structural feature which is formed by the intersection of the northern section of the Cincinnati Arch with the Findlay Arch to the northeast and the Kankakee Arch to the northwest. Three extensive basins surround the arch structures; the Appalachian, Michigan, and Illinois Basins to the east, north, and west, respectively (see Figure 1). Approximately 1 km of flat-lying lower Paleozoic Cambrian, Ordovician and Silurian rocks overlie the Precambrian basement of the Indiana-Ohio Platform. The Paleozoic section thickens toward the basins with an increase in thickness of the lower Paleozoic formations and the addition of younger layers. The basins contain up to 3500 meters of Paleozoic and younger strata. Three to 150 meters of glacial drift form the surface above the youngest paleozoic rocks. Glacial drift completely controls the topography. The preglacial Teays river, which was approximately the size of the present-day Ohio River, flowed SE-NW in the Anna region, and left channels up to 50 meters deep which are preserved on the buried bedrock surface (VerSteeg, 1946; Forsyth, 1956; Cummins, 1959). These buried channels align with the postulated Anna-Champaign fault, and thus may have been fault controlled locally. Depth to bedrock information from 4259 water wells and 84 gas and oil wells are contoured in Figure 2 and clearly indicate the course of the Teays river and its tributaries.

It has been suggested that the Grenville Front which is the N-S trending Precambrian lithologic/structure contact between the older Superior province to the west and Grenville province to the east, lies approximately 20-30 km east of the Anna area (see Bass, 1961; Owens, 1967). This front is in some places a fault and in other places a metamorphic transition zone. Basement rocks just east of the front have been described as predominantly medium to high grade metamorphic, while to the west there are essentially unmetamorphosed igneous rocks. The evidence that the Grenville Front passes through western Ohio is based on a small number of wells (mostly oil) which penetrate into the Precambrian basement and also on the interpretation of magnetic and gravity anomalies. The observed lithologies and ages of drilling chips seem to be consistent with such a conclusion; however, the evidence is not conclusive. Lithologic data collected from deep oil wells indicate that the Anna area is underlain by a laterally variable basement complex. The basement rocks in Indiana and western Ohio are either granites or extrusive

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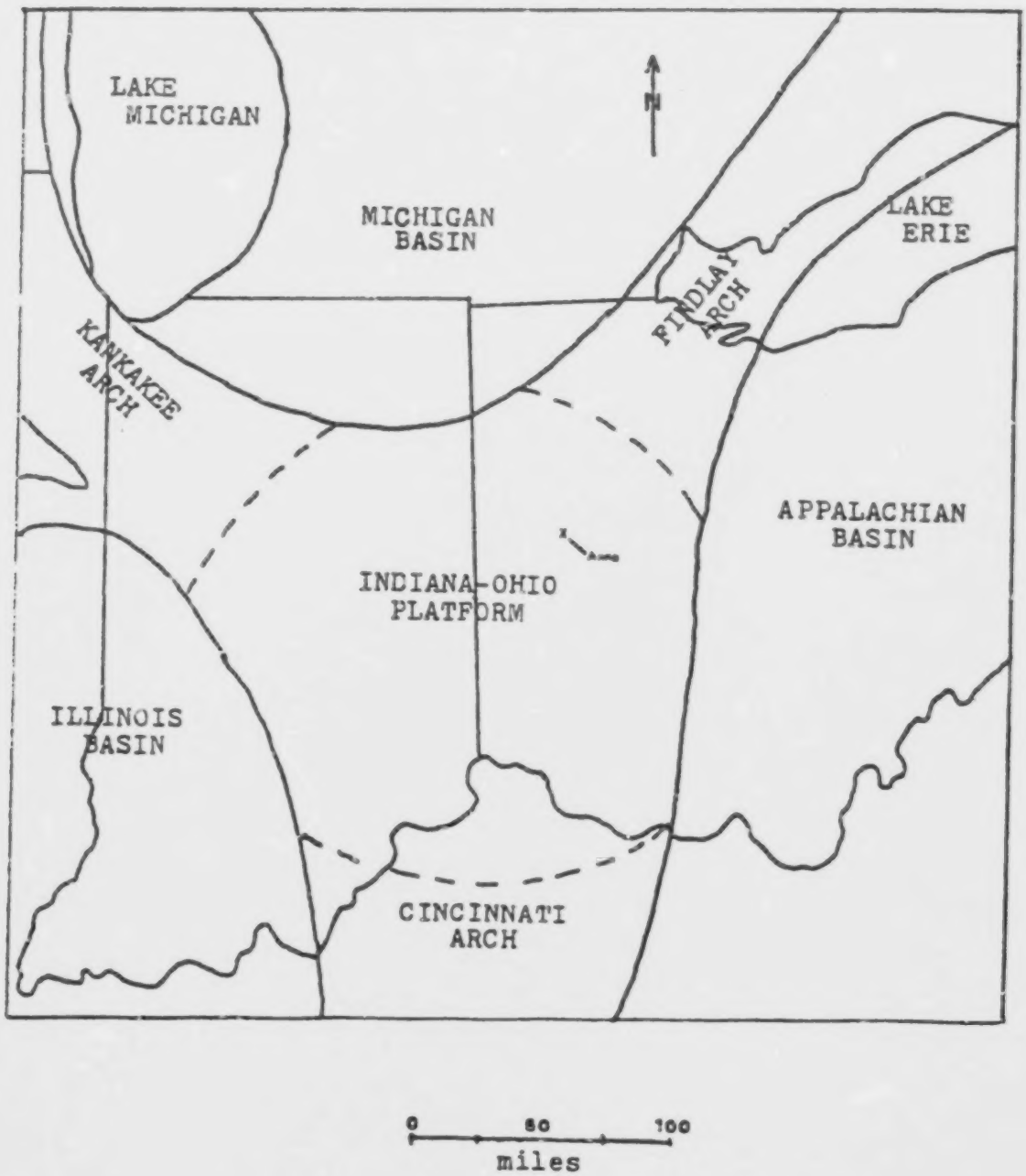


Figure 1. Distribution of the Basin and Arch Structure in the Precambrian Surface of Indiana and Ohio (after King, 1969, as found in Heidorn, 1979).

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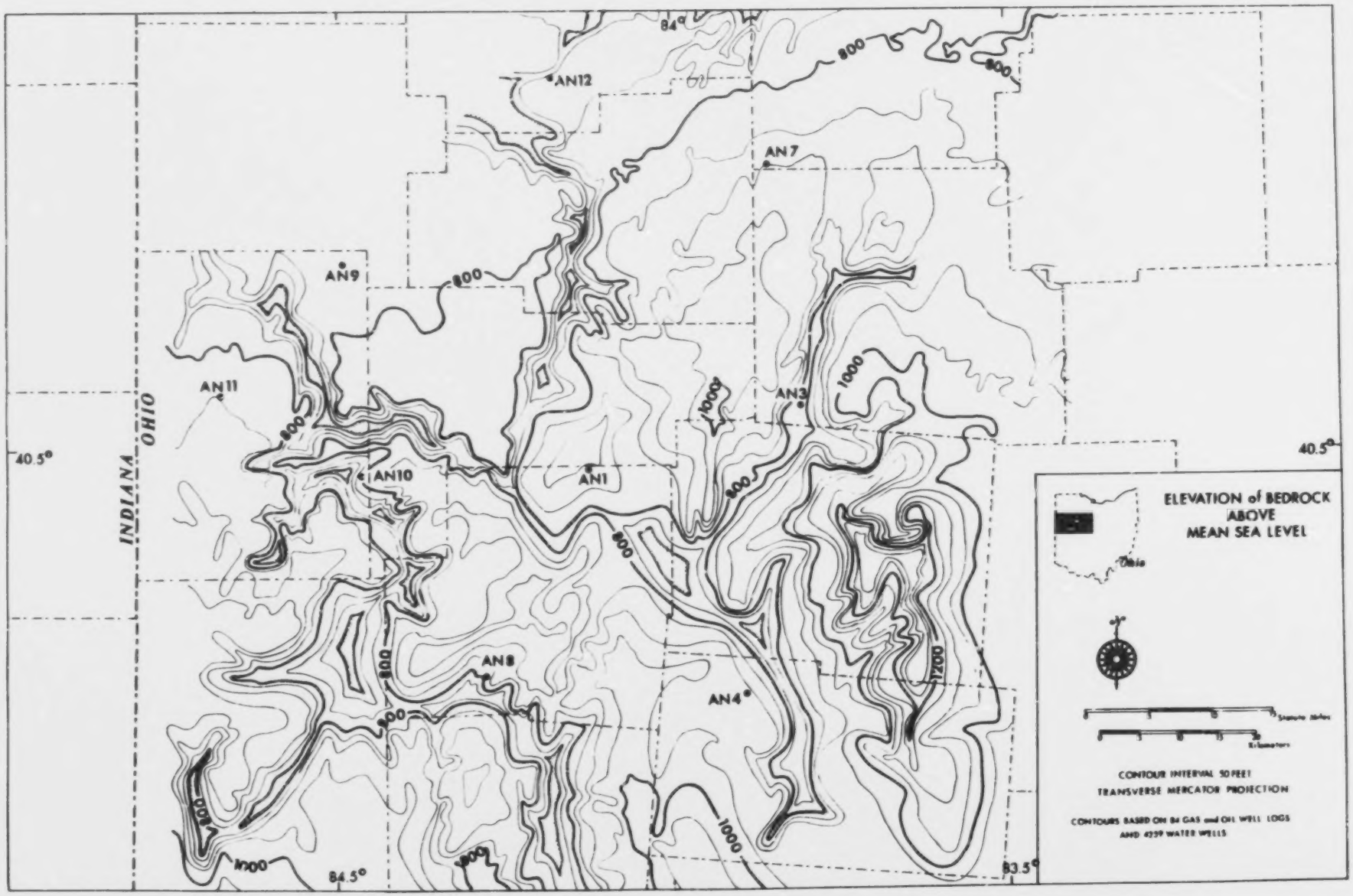


Figure 2. Elevation of Bedrock above Mean Sea Level.

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rocks. East of this zone in central Ohio the lithologies are predominantly high-grade metamorphic rocks of the Grenville Province. Isotopic age dates indicate an abrupt increase in the age of the rocks from east to west in western Ohio. Directly beneath the town of Anna igneous extrusives dominate the upper basement. Figure 3 shows the proposed location of the Grenville Front in Ohio from Bayley and Muehlberger (1968). A recently published aeromagnetic map (Hildenbrand and Kucks, 1984) shows N-S trending magnetic highs which run the entire length of central Ohio. This anomaly has been suggested to be the remains of an ancient rift zone or perhaps the signature of the Grenville Front (see Keller et al., 1982 and 1983).

Additional information and references on the geology and basement structure in the Anna region can be found in Rudman et al. (1965), Janssens (1973), Berry and Fuchs (1973), Kiefer and Trapp (1975), Hinze et al. (1977), Jackson et al. (1981), Christensen et al. (1983), and Braile (1986).

Proposed Faults

Three faults which have been postulated to occur in the Anna Seismic Zone are shown in Figure 4. None of these three are exposed at the surface, as the inferred faults are overlain by 15 to 70 meters of glacial till, nor have they been described in the open literature. The existence of these faults was interpreted by A. Patterson of ANSU Corporation of Columbus, Ohio, from proprietary geophysical data and presented at a professional meeting (Thompson et al., 1976). These faults have been reproduced in two engineering reports by Stone and Webster (1976) and Dames and Moore (1975). Interpretations of basement faulting have also been prepared by Stead (1975) based on Patterson's work, Kiefer and Trapp (1975), and independently by McGuire (1975) by modeling magnetic data. The faults inferred in this and previous annual reports (see Figure 4) are a compilation of reliable information from the above sources. The seismicity shown in Figure 4 will be described later in this report.

The Anna-Champaign fault, near or on which the Anna earthquakes appear to have occurred, is the most prominent of the three postulated faults. It trends NW-SE with up to 150 feet of downthrow to the northeast. Proprietary seismic reflection data were obtained by two traverses across the fault by American Pacific International, Inc. (Stone and Webster, 1976). The fault was conjectured from a previous gravity survey by Patterson from the gravity residual map of a survey conducted by ANSU Corporation. The gravity map indicated a NW-SE trending fault downthrown to the north. The seismic surveys confirmed the presence of this fault (Stead, 1975). Magnetic data (McGuire, 1975) suggested the presence of two faults, one closely paralleling the Anna-

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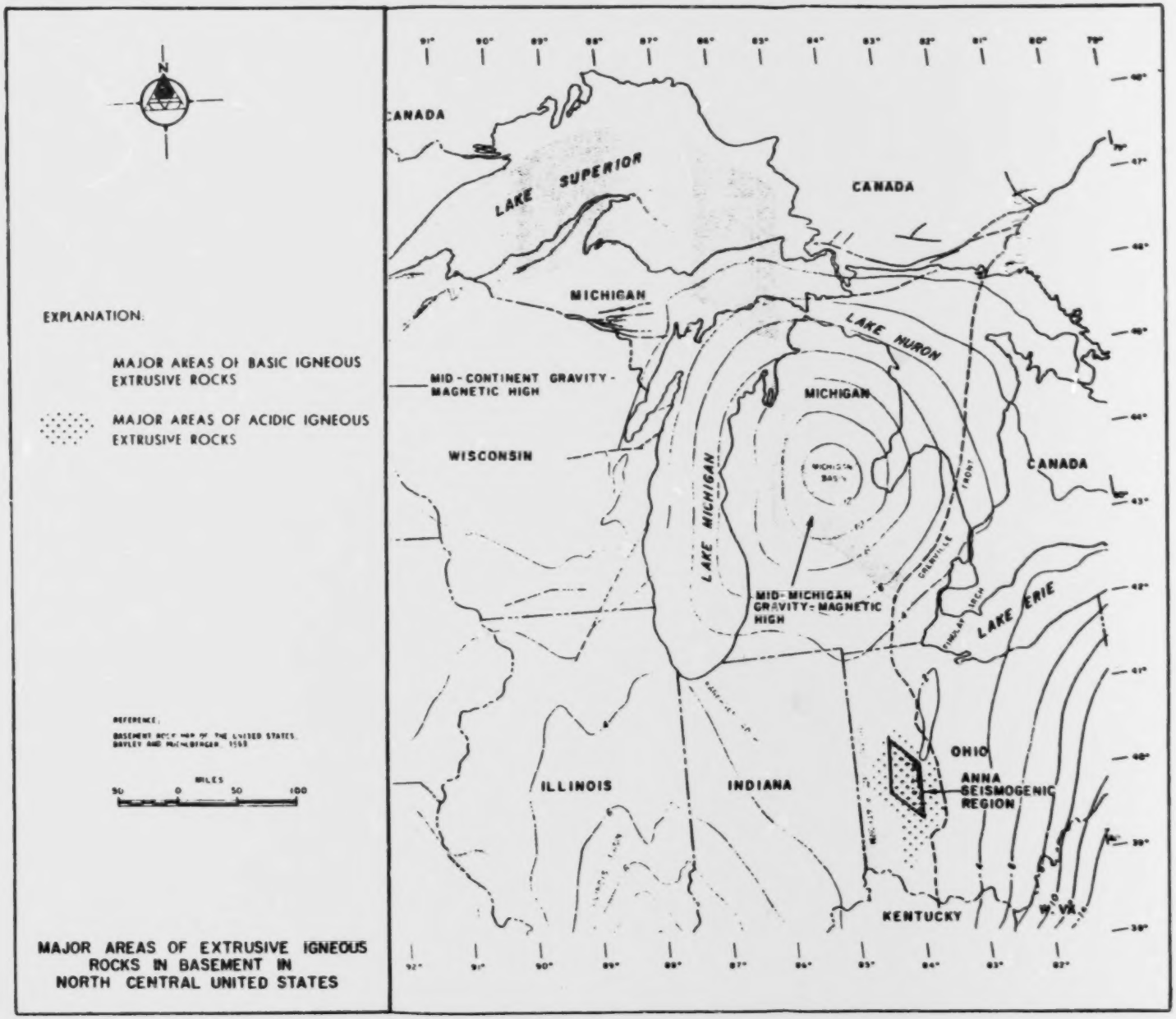


Figure 3. Basement Structure in North Central United States (from Bayley and Muehlberger, 1968).

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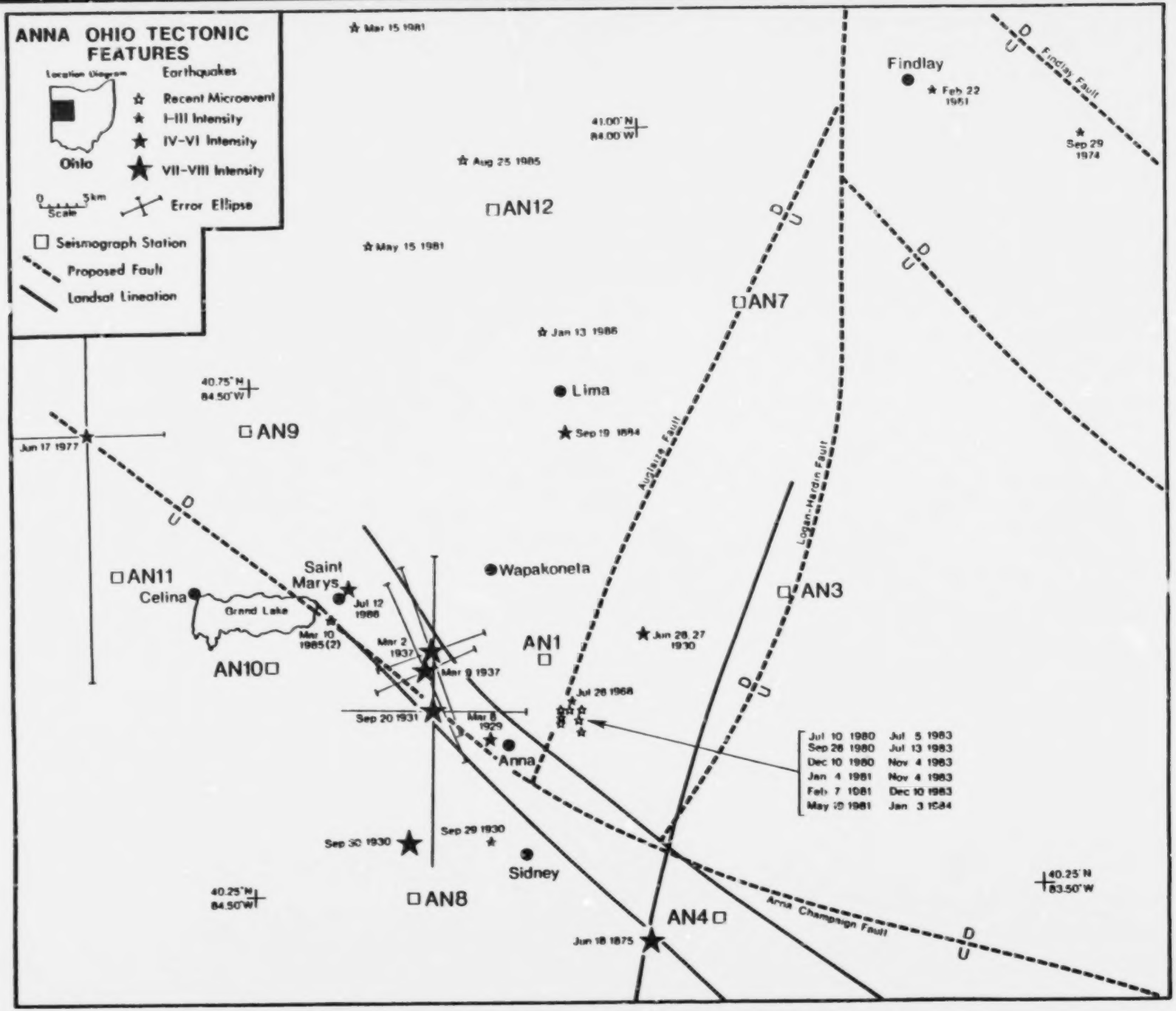


Figure 4. The Anna, Ohio Seismic Zone, Historical Seismicity, Proposed Faults, and Observed LANDSAT Lineaments.

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Champaign fault and one paralleling 15 km northeast of the Anna-Champaign fault.

The Logan-Hardin fault, trending NE-SW was inferred from proprietary seismic data and confirmed by well log data. The down-thrown side is to the west, with 8 to 16 meters of displacement (Stone and Webster, 1976; Stead, 1975). This fault has been postulated as the southern extension of the Bowling Green fault, a N-S trending fault which is exposed in Wood County to the north (Stead, 1975). The third postulated fault, the Auglaize, trends NE-SW, with the downthrown side to the west, and is based on well data alone. The displacement is approximately 15 meters.

Very prominent lineaments have been found on false color LANDSAT imagery which were close to the Anna-Champaign and Logan-Hardin postulated faults, as shown in Figure 4. Remote sensing lineament tracing is a reconnaissance procedure which should be viewed warily; however, many unmapped faults and fracture systems have been discovered from LANDSAT imagery. In this case the three lineaments shown in Figure 4 as solid lines are very prominent and pervasive. In several instances small streams change course and become trapped in these lineaments. Two lineaments trending NW-SE bracket Anna and the Postulated Anna-Champaign fault. The third LANDSAT lineament trends approximately N-S in the vicinity of and closely paralleling the postulated Logan-Hardin fault. This lineament also coincides with an island chain in Indian Lake.

The relationship between the surficial LANDSAT lineaments, the buried Teays river valley, the inferred faults which are believed to be in the Paleozoic section, and recent recorded earthquakes which all appear to occur below the Paleozoic strata in the Precambrian basement (between 5 and 10 km) is still unclear, although it is probably safe to assume that the surficial features are probably being controlled by deeper trends.

Further information and additional references about the geology and basement structures of the Anna region can be found in earlier annual reports by Jackson et al. (1981) and Christensen et al. (1983).

II
THE WESTERN OHIO - INDIANA SEISMIC ARRAY

The Western Ohio - Indiana seismic network currently consists of thirteen local and two regional (ACM, AAM) short period vertical stations. The thirteen local stations are formed by the original nine stations of the Anna, Ohio network, fully operational since June 1978, and a sub-network of four stations located in Indiana which were installed in February 1981. Locations, elevations, magnifications and other station information are listed in Table 1 and the station locations are shown in Figure 5. The array has been upgraded and redesigned on several

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TABLE 1

STATION CHARACTERISTICS OF THE OHIO-INDIANA SEISMIC ARRAY

Station Code	Lat.°N	Long.°W	Elevation (Feet)	Displacement Gain (Peak)	Carrier (MHz) (x1000)	Subcarrier (Hz)
AN1	40.4792	84.1309	1003.	246.7	164.0093	1700
AN3	40.5489	83.8121	1070.	246.7	165.8093	1400
AN4	40.2222	83.8978	1134.	493.5	173.1940	1400
AN7	40.8235	83.8602	922.	493.5	171.4060	1700
AN8	40.2441	84.2860	992.	246.7	166.4218	680
AN9	40.7118	84.4967	835.	246.7	167.8090	2040
AN10	40.4729	84.4700	901.	246.7	167.1937	1020
AN11	40.5638	84.6804	895.	246.7	166.6565	1020
AN12	40.9217	84.1823	741.	493.5	163.7937	2040
IN1	40.542	85.894	837.	342.6	phone line	680
IN2	39.939	86.783	872.	342.6	phone line	1020
IN3	39.265	85.785	722.	342.6	phone line	1400
IN4	39.570	84.903	1025.	342.6	phone line	1700
ACM	42.6475	85.8517	880.	342.6	phone line	1700
AAM	42.2997	83.6561	817.	12.5	direct recording	

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Figure 5. Station Locations for the Ohio-Indiana Seismic Array.

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occasions during its decade of operation. The majority of these changes have been in the field equipment. The original design included Mark Products L-4C, 1 hz geophones and Interproducts Amplifier/VCO (Voltage Controlled Oscillators) which were powered by non-rechargeable battery packs. All data were transmitted by direct data phone lines. The four Indiana stations and station ACM in western Michigan are still operating on this original design. The nine Ohio stations have undergone various transformations. Radio telemetry was installed to alleviate phone line charges. However, the increased power necessary for the radio transmitters required a larger power supply which was finally satisfied using a battery-solar power recharge system. The instrumentation at the Ohio stations has also changed over the years, with the original Mark Products L-4C geophones being replaced by Geospace HS-10, 1 hz geophones and then finally replaced by the new Teledyne S-500, 1 hz geophones. The VCOs have also been replaced with the much more stable Teledyne 42.50-1 and 46.22 Amplifier/VCO. The rechargeable batteries were also replaced in 1986 after about seven years of service.

The nine west-central Ohio stations are currently designed as shown schematically in Figure 6a. The data from these stations are transmitted by radio to a central tower at Wapakoneta, Ohio. The four Indiana stations are designed as shown schematically in Figure 6b and the data transmitted by telephone link to the receiving facility at Wapakoneta, Ohio. The receiving facility at Wapakoneta, Ohio is shown schematically in Figure 6c. At this facility, signals from the thirteen Ohio and Indiana stations are multiplexed onto three trunk lines and transmitted to the recording facility at the University of Michigan in Ann Arbor, Michigan. The recording facility is shown schematically in Figure 6d. Individual station data are discriminated from the multiplexed signal and recorded at the University of Michigan.

The full system response curve for the Ohio network as calculated from published response characteristics is shown in the unity gain curve in Figure 7a. The response curve for the Indiana stations, and the regional station, ACM, which were calculated through a combination of experimental and published response characteristics, is shown in Figure 7b. The curves in Figure 7 represent the response of the system using a 12.5 hz low pass filter, which is used for the visual pen-and-ink recordings.

During the last fiscal year (October 1985 - September 1986) the stations have been operational approximately 82% of the time. Individual station reliability data averaged for each month of the fiscal year are given in Table 2. Detailed daily station up-times for the fiscal year (October 1985 - September 1986) are listed in Appendix A. Over the complete five year period of the current contract the stations have been operational 87% of the time. Individual station reliability data averaged for each year of the five

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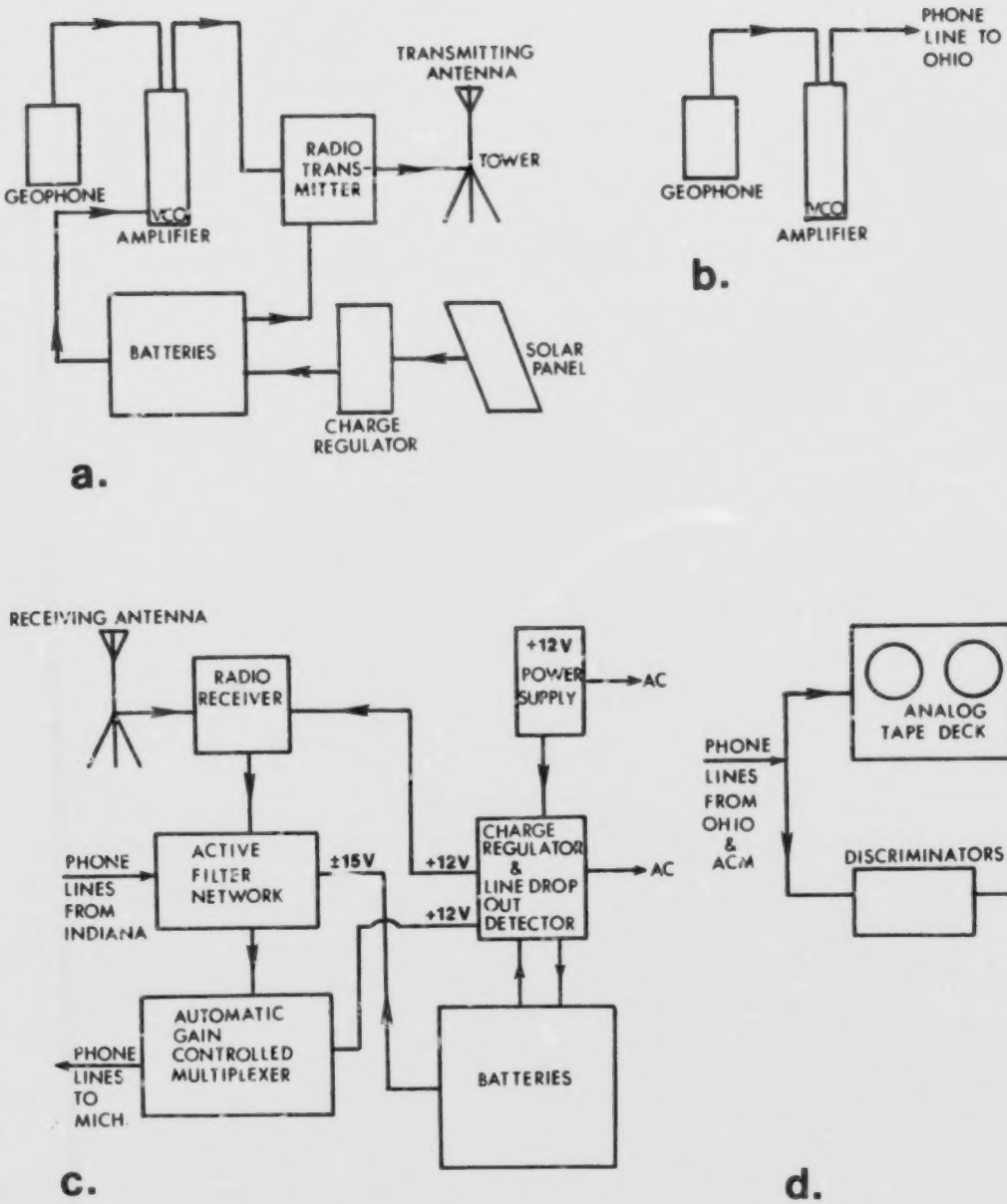


Figure 6. Schematics of Field Installations, Multiplexing and recording facilities (see legend, following page).

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a. GEOPHONE - Teledyne S-500, 1 Hz
AMPLIFIER VCO - Teledyne 42.50-1 and 46.22
RADIO TRANSMITTER - Delco Radio Transmitter
TRANSMITTING ANTENNA - Db Products, 7db gain antenna
TOWER - TRI-X radio tower
Batteries - GNB-Absolite, 12 volt, 100 AH
CHARGE REGULATOR - Solarex SR012075AF, 75 watts
SOLAR PANEL - Solarex 6600/12 Solar cell system with 66 watts DC peak power output

b. GEOPHONE - Mark Products L-4C, 1 Hz, 0.7 critical damping
AMPLIFIER VCO - Interproducts

c. RECEIVING ANTENNAS - Db Products, 7 db gain antennas, mounted on a 300 foot tower
RADIO RECEIVERS - Repco Radio Receiver
ACTIVE FILTER NETWORK
AUTOMATIC GAIN CONTROLLED (AGC) MULTIPLEXER
POWER SUPPLY - Power Mate PT 15 C.
CHARGE REGULATOR
BATTERIES - MDP5 NICAD

d. ANALOG TAPE DECK - Hewlett-Packard 3964A
DISCRIMINATORS - Teledyne Geotech 46.12
RADIO - Kinemetrics Model WVTR Mark IV
CLOCK - Teledyne Geotech TG-120
RECORDING DRUMS - Sprengnether, VR-65-3 (3) and VR-55-3 (2)
PDP 11 DIGITAL COMPUTER - DEC PDP-11 Model 23 Minclab digital computer

Figure 6 (Legend)

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Response Curve	Pen Amplifier Setting	Peak Magnification
(a)	100 mv/mm	493.5k
(b)	100 mv/mm	342.6k

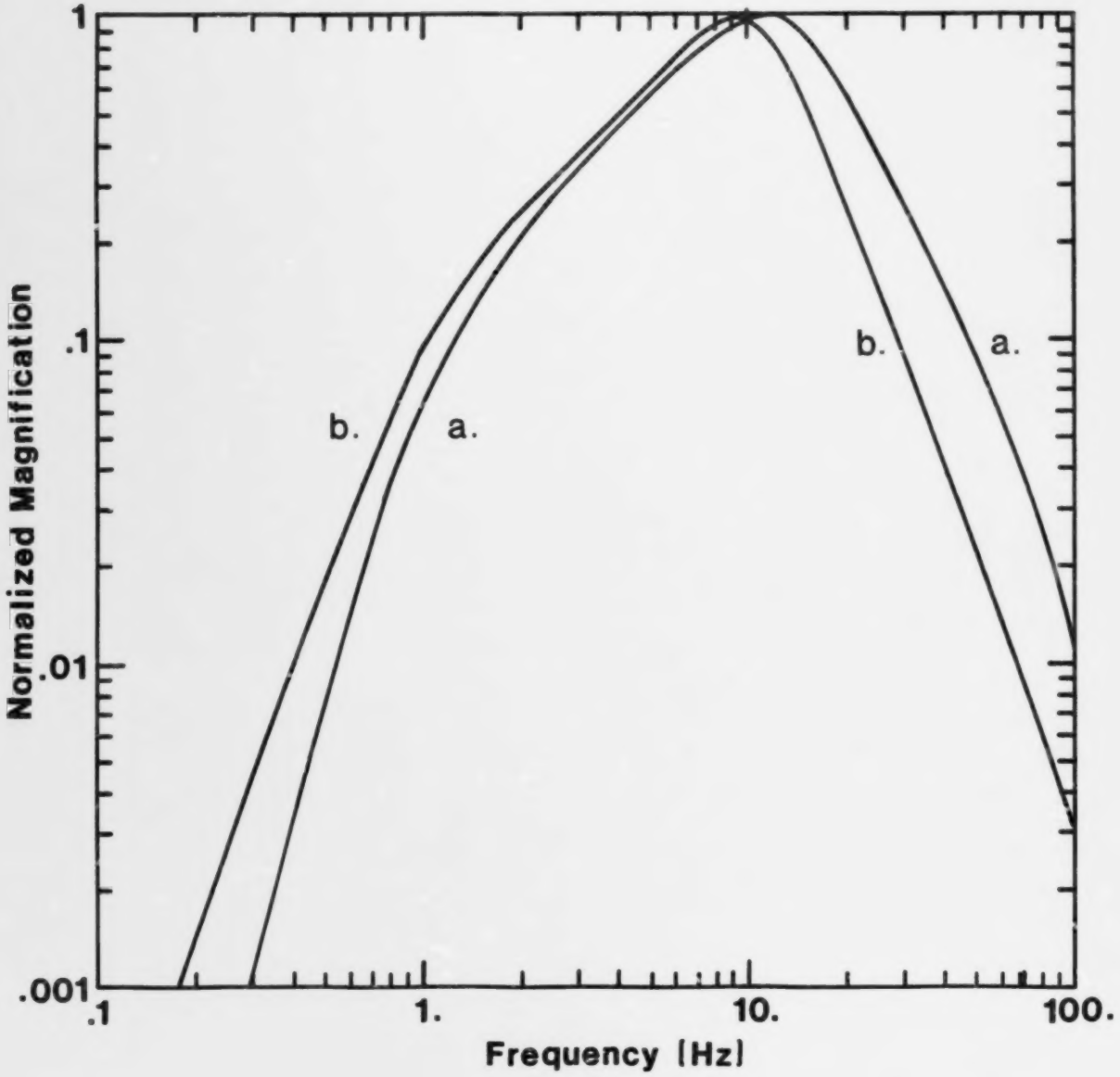


Figure 7. Normalized System Frequency Responses for (a) Ohio stations - S-500 seismometer, and for (b) Indiana stations and ACM - L-4C seismometer.

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TABLE 2

STATION RELIABILITY DATA (%)

Monthly Summary	Stations AN1	AN3	AN4	AN7	AN8	AN9	AN10	AN11	AN12	IN1	IN2	IN3	IN4	ACM	Monthly Total
OCT 1985	100	99	95	86	0	96	95	99	98	82	60	80	82	99	84
NOV 1985	100	100	97	98	0	98	98	100	100	98	98	0	98	100	85
DEC 1985	97	100	96	99	0	99	99	99	100	100	93	0	100	99	84
JAN 1986	100	100	94	100	0	100	100	100	100	99	99	0	99	99	85
FEB 1986	93	86	85	99	0	98	99	99	78	100	100	0	91	93	80
MAR 1986	95	41	98	99	0	100	100	100	45	98	98	63	100	99	81
APR 1986	87	0	100	100	0	97	98	99	100	99	12	100	100	100	78
MAY 1986	98	0	95	62	50	99	98	99	100	100	49	100	97	99	82
JUN 1986	98	0	98	64	93	99	99	100	99	99	99	99	97	15	83
JUL 1986	36	48	81	77	98	75	88	100	94	97	91	70	100	0	75
AUG 1986	5	100	99	100	100	100	100	100	98	95	84	0	63	65	79
SEP 1986	86	100	100	97	100	78	100	100	100	100	97	72	58	99	92
Station Total	83	64	95	90	37	95	98	100	93	97	82	49	90	81	Total 82

TABLE 3

STATION RELIABILITY DATA (%)
(Fiscal year runs from October 1 through September 30)

Yearly Summary	Stations AN1	AN3	AN4	AN7	AN8	AN9	AN10	AN11	AN12	IN1	IN2	IN3	IN4	ACM	Yearly Total
1981-82	70	90	91	91	97	93	77	97	89	93	95	96	68	43	85
1982-83	98	98	96	90	98	98	91	97	96	94	82	85	97	94	94
1983-84	99	88	84	95	98	99	74	99	56	97	86	66	65	81	85
1984-85	88	98	92	85	54	96	77	81	84	90	77	93	99	98	87
1985-86	83	64	95	90	37	95	98	100	93	97	82	49	90	81	82
Station Total	88	88	92	90	77	96	83	95	84	94	84	78	84	79	Total 87

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year effort are given in Table 3. The downtime reflected in the above-mentioned reliability data includes both periods of instrumental failures (e.g. mechanical breakdown) and periods in which the records were not interpretable due to other factors (e.g. weather, cultural noise, etc.).

Further descriptions of the Anna array instrumentation can be found in previous annual progress reports by Mauk et al. (1979, 1980), Jackson et al. (1981), and Christensen et al. (1983).

III
HISTORICAL SEISMICITY

A central United States historical seismicity map such as that of Nuttli and Herrmann (1978) demonstrates that, although activity is generally low, there are several spatially restricted regions where both earthquake recurrence rates and observed magnitudes are relatively high. The seismically active zone in western Ohio, frequently referred to as the Anna, Ohio Seismic Zone is one of the most enigmatic of these regions. Bradley and Bennett (1965) compiled a list of seventy-eight earthquakes known or suspected to have occurred in Ohio between 1776 and 1964. About one third of these occurred in the Anna region with the remaining two thirds spread throughout the state but occurring mostly in the northern and western portions of the state. The data from Bradley and Bennett (1965) were derived principally from regional newspaper accounts from which maximum local earthquake intensities can frequently be estimated, but from which accurate earthquake epicenters and magnitudes can rarely be determined. Nuttli and Herrmann (1978) published a revised table of Anna earthquakes extending from 1895 through 1974 which listed improved estimates of origin times, locations, felt areas, maximum intensities and magnitude. Subsequently, Nuttli and Brill (1981) reexamined seismograms of Anna earthquakes with magnitudes larger than 3.5 listed in the Nuttli and Herrmann catalog. It is important to realize that the majority of these entries occurred prior to 1925 when few seismograph stations existed and precision timing was not possible. The utility of such a table is therefore more qualitative than quantitative, demonstrating the relatively high earthquake recurrence rates in the Anna Seismic Zone and that events as large as magnitude 5.0 have occurred. The uncertainty of earthquake locations prevent the data from being used to identify geological structures from which the activity originates. The epicentral locations for the more reliable historical data are illustrated on a map of the Anna Seismic Zone in Figure 4. The sizes of the stars are related to the maximum intensities. The locations of events on Figure 4 should be considered only approximate unless location error bars (from Dewey and Gordon, 1984) are attached to the

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symbols. Other information on this figure will be discussed later in this report.

Earthquakes known or suspected to have had magnitudes up to 5.0 occurred on June 18, 1875, and March 9, 1937, Only the earthquakes of September 20, 1931, March 2, 1937, and March 9, 1937 have adequate recorded instrumental data to permit reevaluation of hypocenter parameters. Isoseismal maps of the March 2, and 9, 1937 earthquakes are illustrated in Figure 8 after Westland and Heinrich (1940). These earthquakes have been relocated using the JHD method by Dewey and Gordon (1984). Their revised epicentral locations and 95% location confidence error ellipse axes are illustrated in Figure 4. The only other large magnitude earthquake having data marginally adequate for relocation is the September 20, 1931 earthquake which is also illustrated with 95% location error ellipse axes on Figure 4.

There is additional information which suggests that the March 2 and 9, 1937 earthquakes may actually be located to the east of their relocated position by 5 to perhaps 15 km. This new location would shift the epicenters outside the 95% error ellipse and would require that there be some systematic bias to the relocations of Dewey and Gordon (1984). This new information comes from a letter written to Reverend Victor C. Stechschulte by Jacob E. Zint who ran a set of seismometers in Wapakoneta, Ohio during the 1937 events. Zint reports in his letter that the first motions for both the 1937 events were to the north and west (in Zint's words "the ground moved from south-southeast to north-northwest"), and includes a detailed drawing of his seismographic system. These first motions would require that the events be located in the northwest or southeast quadrants from Wapakoneta, whereas the current locations are in the southwest quadrant. The southeast quadrant is most likely since it is closer to the area around Anna, Ohio where most of the damage occurred. This new location may suggest that the 1937 events (and maybe the 1931 event) are actually located near a region, northeast of Anna, Ohio, in which recent microseismic activity has been recorded.

IV
LOCAL AND NEAR REGIONAL EVENTS

During the report period (October 1985 - September 1986) five earthquakes were recorded in the region. The location of these events are shown in Figure 9, and their origin times, epicenters, and estimated magnitudes listed in Table 4. The magnitudes of these events range from 0.5 to 5.0m_b. The two largest of these events (January 31 1986 near Cleveland, Ohio, magnitude = 5.0m_b; also known as the Perry earthquake, and July 12, 1986 near St. Marys, Ohio, magnitude = 4.5m_b) were felt with minor damage reported in each case. The Perry earthquake near Cleveland, Ohio is the largest to occur in the region since the Sharpsburg,

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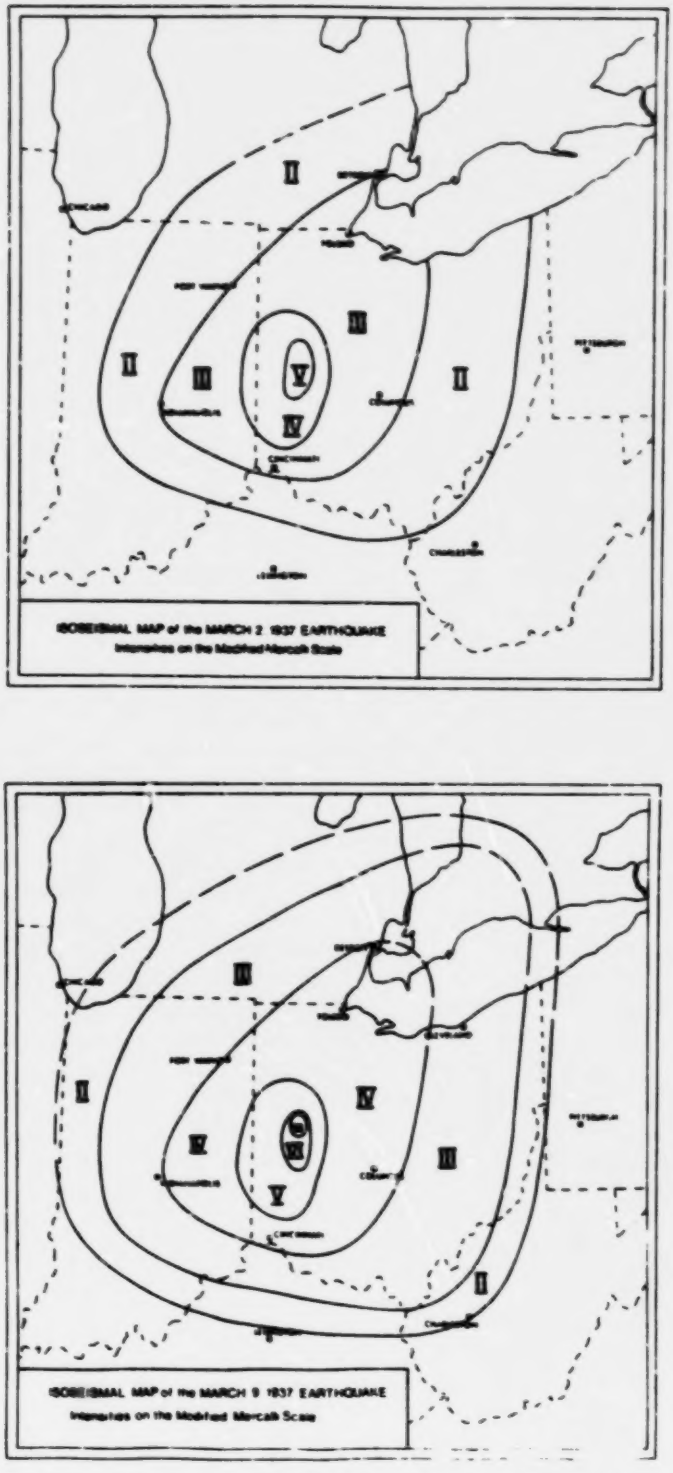


Figure 8. Isoseismal Maps of the March 2, and March 9, 1937, Anna, Ohio Earthquakes (after Westland and Heinrich, 1940, as found in Heidorn, 1979). Locally in the epicentral regions intensities have been reported as high as VII for the March 2, 1937 earthquake, and VIII for the March 9, 1937 earthquake.

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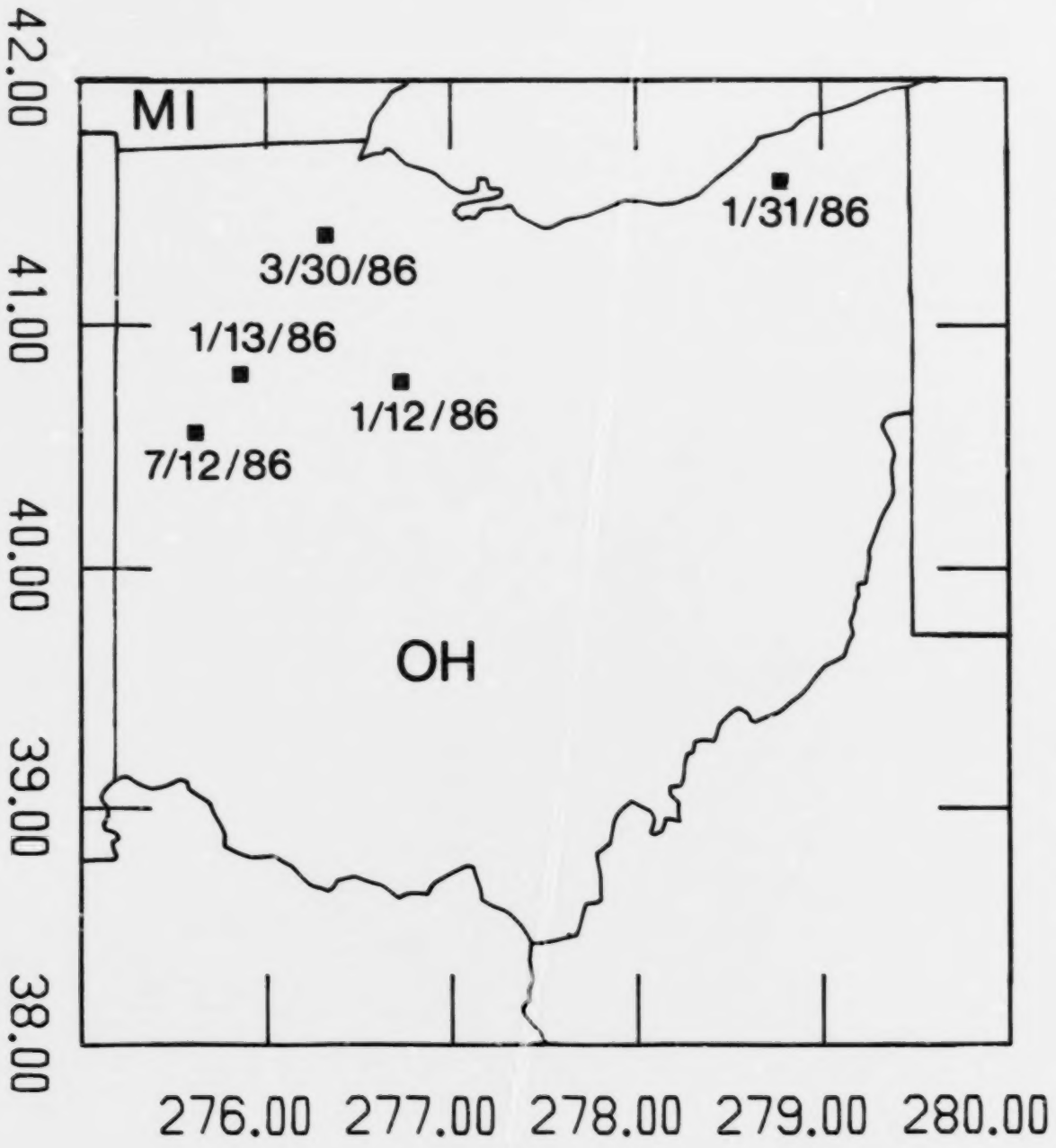


Figure 9. Local and Near-Regional Earthquake Locations from October, 1985 through September, 1986.

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TABLE 4

LOCAL AND NEAR-REGIONAL EVENTS FROM
OCTOBER 1985 THROUGH SEPTEMBER 1986

Date Year	Mo	Da	Origin Time Hr Mi Sec (GMT)	Location Lat. °N	Long. °W		Magnitude (duration)	Depth (km)
1986	01	12	11:38:50.2	40.77	83.27		0.8	--
1986	01	13	11:39:20.4	40.80	84.13		0.5	--
1986	01	31	16:46:41.4	41.59	81.21	(NEIS)	5.0 m_b	--
1986	03	30	07:42:42.1	41.37	83.67		1.4	--
1986	07	12	08:19:39.0	40.56	84.37		4.5 m_b	5-10

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Kentucky earthquake on July 27, 1980 (magnitude = 5.1m_b), while the St. Marys earthquake is the largest to occur in the Anna Seismic Zone since the historic events on March 2 and March 9, 1937 (magnitude = 4.5 and 4.9, respectively).

The January 31, 1986 Perry earthquake has been studied in detail by several groups (Wesson and Nicholson, 1986; Seeber, 1986; Stover, 1986). The focal mechanism determined by the Harvard group (from the PDE report) is shown in Figure 10 and an isoseismal map of the event from Stover (1986) is shown in Figure 11. Further information on this event can be found in the above references.

The July 12, 1986 St. Marys earthquake occurred near the town of St. Marys which is about 25 km northwest of Anna, Ohio. The focal mechanism for this event has been determined using first motion data from 79 local and regional stations and is shown in Figure 12. This mechanism represents mostly strike-slip motion with nodal planes striking NW-SE and SW-NE. The compressional stress axis is oriented approximately E-W and horizontal and agrees with the regional stress directions as determined by Sbar and Sykes (1973). The focal mechanism for the St. Marys event is also very similar to the focal mechanism for the Perry earthquake (see Figure 10) and the Sharpsburg earthquake on July 27, 1980 (see Mauk et al., 1982; Herrmann et al., 1982). In addition, the poorly constrained focal mechanism for a small (mag=2.2) event near the town of Anna on July 5, 1983 is also similar to the focal mechanism of the St. Marys event (see Pollack and Christensen, 1984). In the case of the St. Marys earthquake, if we assume that the NW-SE striking plane which is parallel to the proposed Anna-Champaign fault is the fault plane then the motion along the fault is left lateral. An isoseismal map of the St Marys earthquake is shown in Figure 13 (from Carl Stover of the USGS). It is clear from the isoseismal data that the St. Marys event, while being of similar size to the 1937 events, occurred in a distinctly different region than the 1937 events. The St. Marys earthquake is located near the trace of the Anna-Champaign fault and between the June 17, 1977 (m_b=3.3) Celina earthquake (to the northwest) and the relocated historic events in 1937 (to the east-southeast). All of these events occurred near the Anna-Champaign fault and are spread out in a NW-SE direction, suggesting that the Anna-Champaign fault may be the active feature for these larger events in the Anna Seismic Region. The remaining three 1986 earthquakes all occurred in Ohio, but north of the array.

There have now been a total of 42 local and near regional events recorded by the Ohio-Indiana array since its initiation in 1976. Eleven events occurring in Illinois, Indiana, Kentucky, and Ohio were felt. The two largest events during this time period, the July 27, 1980, Sharpsburg, Kentucky (m_b=5.1) and the January 31, 1986, Perry, Ohio (m_b=5.0) have been described in detail in various other reports (Mauk et al., 1982; Herrmann et al.,

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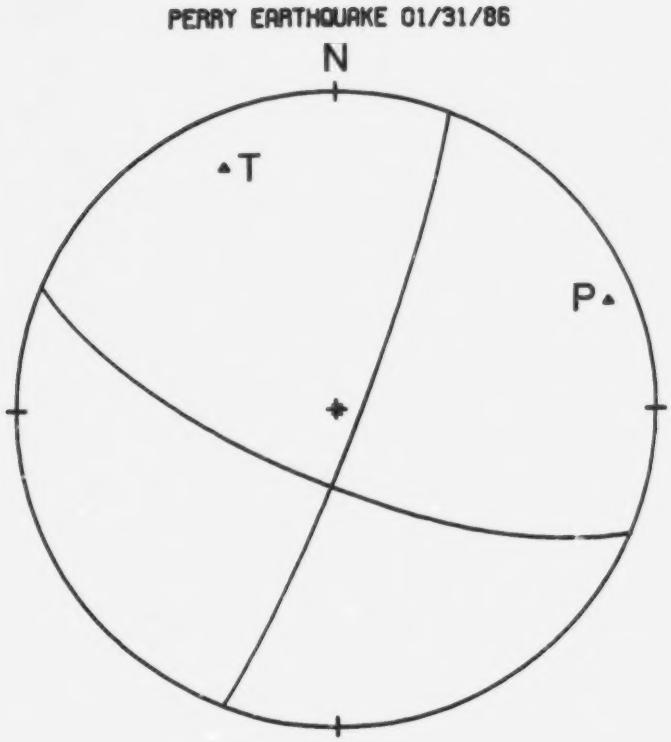


Figure 10. Focal Mechanism for the January 31, 1986 Perry Earthquake Near Cleveland, Ohio (from the Harvard group as found in the PDE monthly listing). The compressional (P) and tensional (T) axes are shown.

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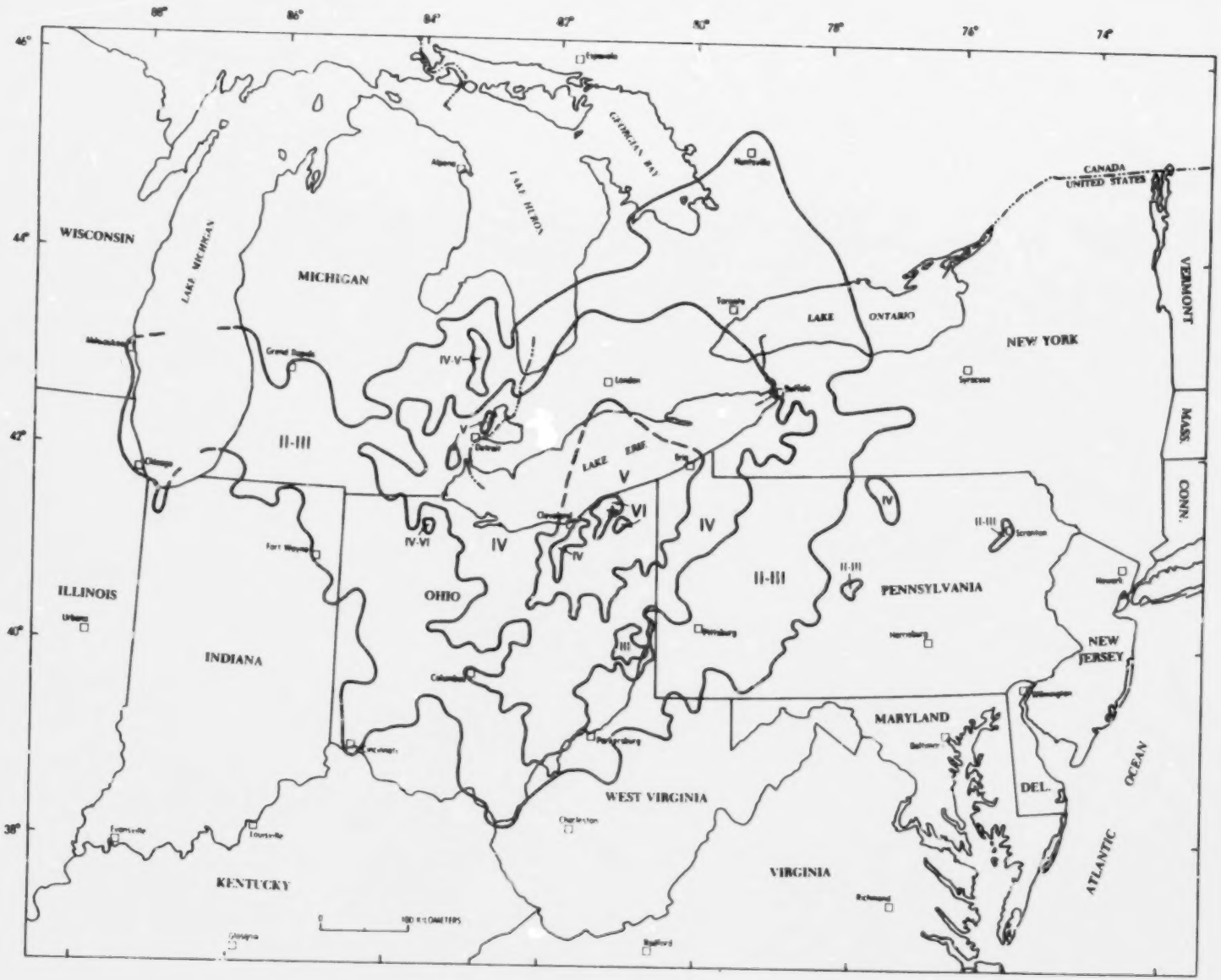


Figure 11. Isoseismal Map for the January 31, 1986 Perry Earthquake (from Stover, 1986).

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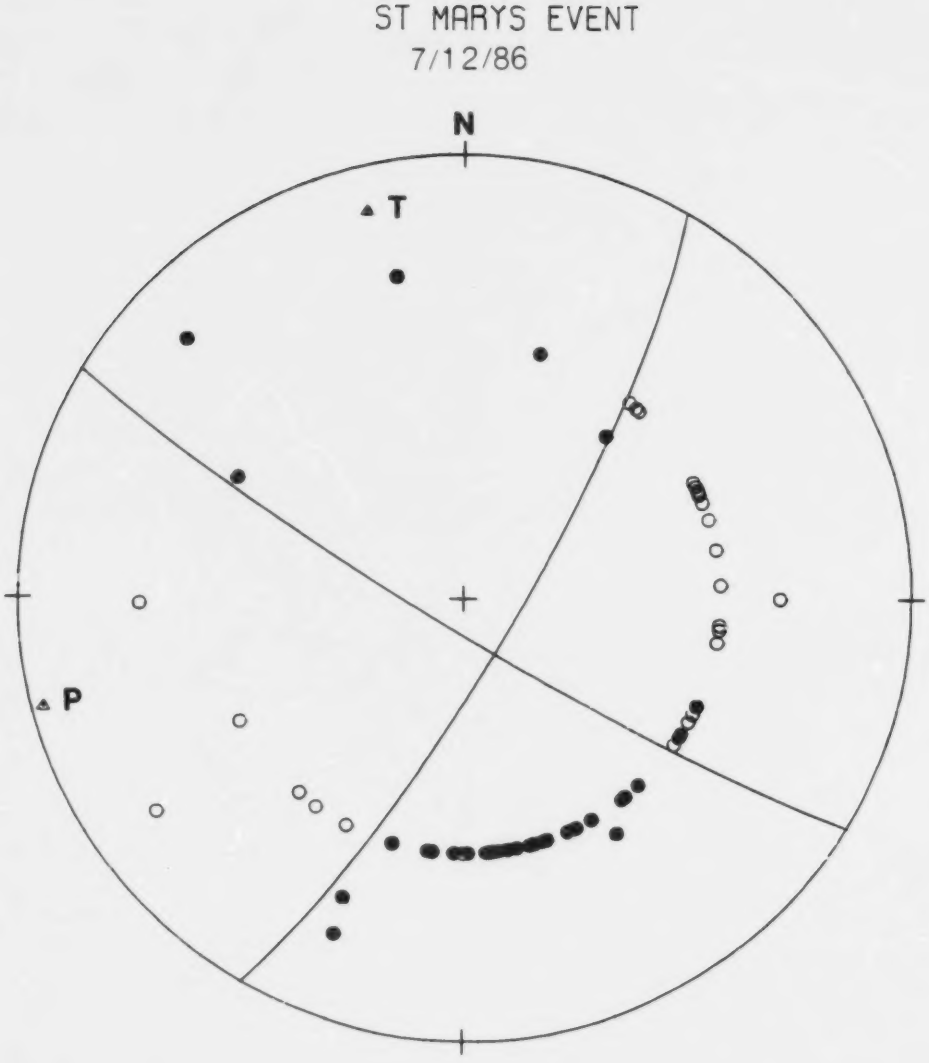


Figure 12. Focal Mechanism for the July 12, 1986, St. Marys, Ohio Earthquake. Compressional arrivals are shown as solid symbols and tensional as open symbols. The P and T axes are also shown.

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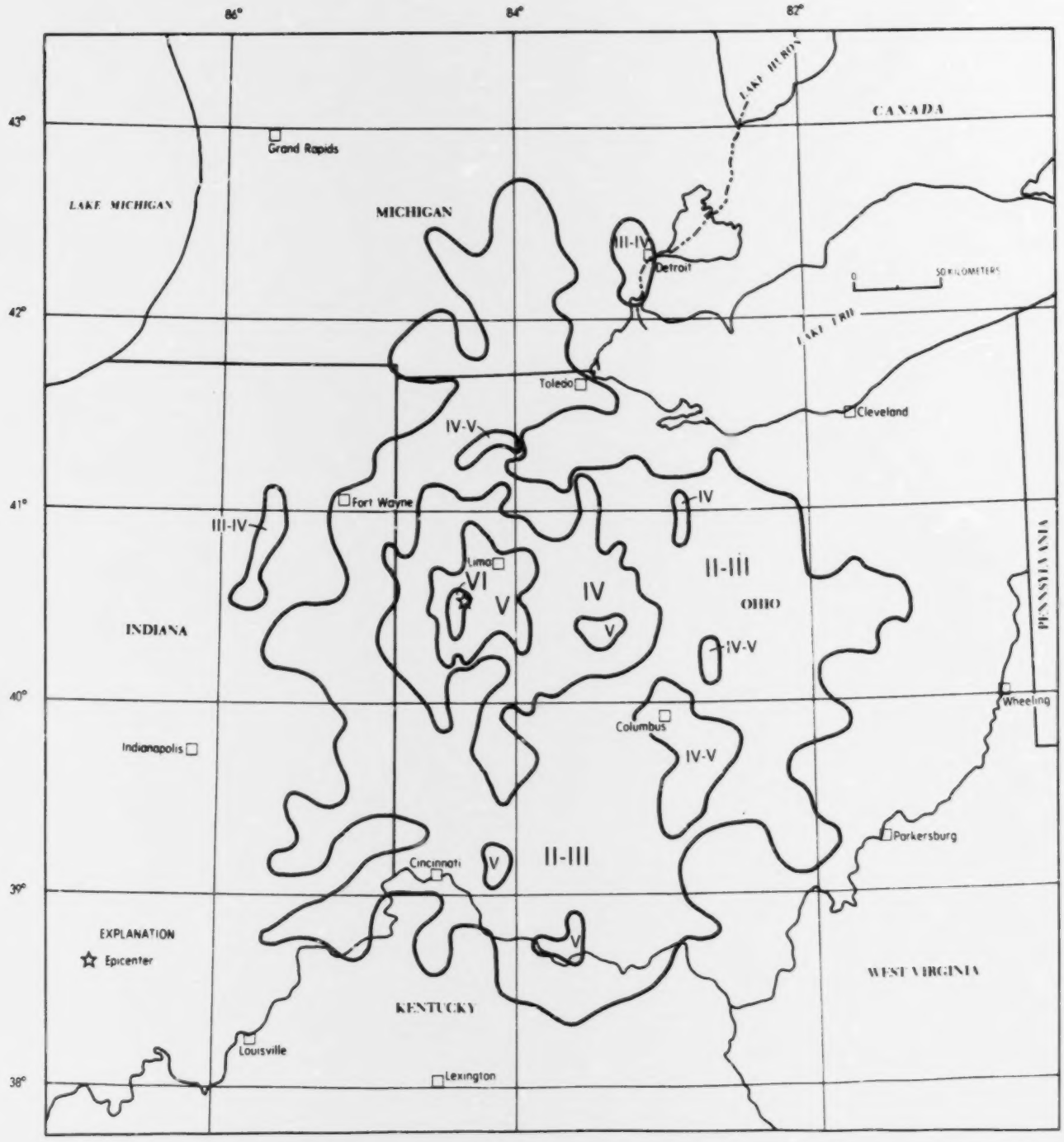


Figure 13. Isoseismal Map for the July 12, 1986, St. Marys, Earthquake (from C.W. Stover, U.S.G.S.)

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1982; Wesson and Nicholson, 1986; Seeber, 1986; Stover, 1986).

A complete listing of all local and near-regional events located by the University of Michigan since 1977 can be found in Table 5; the events are displayed in Figure 14. Events in the west-central Ohio region are illustrated in Figure 4. The arrival times used in the epicentral determinations of the events in Table 5 are listed in Appendix B of this report.

V
TELESEISMIC EVENTS AND P-WAVE RESIDUALS

Teleseismic phase arrivals have been tabulated for over 900 events since June 1978. The phase arrivals for each event recorded by the array between June 1978 and April 1986 are listed in Appendix C of this report. Although these events occur at a variety of azimuths and epicentral distances with respect to the array, most of the arrivals are from events which originate in the southern azimuths (i.e. South and Central America) and in the northwest azimuths (i.e. Japan, Aleutians, and Kuril Islands).

P-wave residuals (observed minus J-B predicted) have been calculated for the above teleseismic events (with epicentral distance < 102°). The calculated residual, back azimuth, distance and return angle for each event which occurred between June 1978 and April 1986 are listed in Appendix D for the nine Ohio stations (including ACM and AAM) and Appendix E for the four Indiana stations.

Average P-wave residuals have been calculated for each station using a hand-picked subset of the recorded events. The events considered have epicentral distances between 20° and 102°. Events with residuals greater than ±4.0 seconds or which have emergent arrivals were not used in the calculations. The average residuals are listed in Table 6 for each station along with the number of values used in the average. The average residuals range from -0.53 seconds at stations ANS, and AAM, to -1.13 seconds at station IN1. Positive residuals reflect slower than average paths and negative residuals reflect faster than average paths. The average teleseismic P-wave residuals are strongly biased by the large number of earthquakes arriving from azimuths to the south and northwest. In order to correct for the azimuthal bias in the averaged P-wave residuals they have also been averaged azimuthally, giving equal weight to arrivals in each 10° azimuth interval. These results are also shown in Table 6. This procedure must also be carefully interpreted because of the high weight which is now given to those azimuth intervals with few arrivals. It must be remembered that while averaging over many events at different epicentral azimuths and distances should tend to remove source and path effects, thereby leaving only local effects in the vicinity of the stations; there are still

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TABLE 5

LOCAL AND NEAR-REGIONAL EVENTS FROM
JUNE 1977 THROUGH SEPTEMBER 1986

Date Year	Mo	Da	Origin Time Hr Mi Sec (GMT)	Location Lat. °N	Long. °W		Magnitude (duration)	Depth (km)
1977	06	17	15:39:47.3	40.57	84.67		3.3 m_b	--
			15:39:46.9	40.705	84.707	(Dewey and Gordon, 1984)		
1979	11	09	21:29:58.7	38.417	82.869	(NEIS)	3.6 m_{bLg}	--
1980	07	10	11:40:53.3	40.415	84.111		0.9	--
1980	07	27	18:52:21.7	38.18	83.94		5.1 m_b	15
1980	08	20	09:34:53.4	41.87	82.99		3.2 m_{bLg}	--
1980	09	26	12:27:25.6	40.430	84.085		0.5	--
1980	10	04	11:46:58.0	39.80	83.75		2.0	--
1980	12	10	02:30:54.3	40.43	84.11		1.2	--
1981	01	04	07:17:37.1	40.418	84.087		1.8	5-7
1981	02	07	05:45:43.0	40.417	84.087		1.8	5-7
1981	03	15	03:46:30.3	41.10	84.35		1.2	--
1981	05	15	23:15:14.0	40.88	84.34		0.8	--
1981	05	19	05:56:11.7	40.407	84.085		1.2	2-8
1982	11	26	08:25:04.9	42.17	85.48		2.0-2.5	--
1983	01	12	02:49:41.1	39.28	84.60		1.9	--
1983	01	22	07:46:59.3	41.86	81.16		2.7 m_{bLg}	--
1983	07	05	02:58:52.9	40.43	84.10		2.1	5-7
1983	07	13	01:17:34.8	40.43	84.10		1.4	--
1983	09	30	02:33:44.8	41.59	84.33		1.3	--
1983	11	04	21:00:59.8	40.43	84.10		0.4	--
1983	11	04	22:50:00.5	40.43	84.10		0.9	--
1983	11	05	02:36:35.8	39.68	85.73		1.1	--
1983	12	03	21:29:41.0	42.70	88.30		1.4	--
1983	12	07	22:57:01.6	41.70	83.50		1.1	--
1983	12	10	19:01:55.2	40.43	84.11		0.7	--
1984	01	03	07:57:58.6	40.42	84.11		0.4	--
1984	01	14	20:14:32.1	41.63	83.44		2.6 m_b	--
1984	07	28	23:39:27.3	39.27	87.09		4.0 m_{bLg}	--
1984	08	29	06:50:59.0	39.25	87.50		3.2 m_{bLg}	--
1984	08	29	18:56:27.2	39.09	87.69		2.7 m_{bLg}	--
1985	03	10	20:46:01.1	40.52	84.39		1.4	--
1985	03	10	20:49:14.1	40.52	84.40		1.7	--
1985	03	17	11:57:06.7	39.65	83.46		1.9	--
1985	04	14	11:39:51.3	41.40	80.37		2.0	--
1985	08	25	14:30:01.6	38.54	84.98		1.6	--
1985	08	25	16:27:11.9	40.97	84.22		1.5	--
1985	09	09	22:06:31.0	41.850	88.006	(NEIS)	3.0 m_{bLg}	--
1986	01	12	11:38:50.2	40.77	83.27		0.8	--
1986	01	13	11:39:20.4	40.80	84.13		0.5	--
1986	01	31	16:46:41.4	41.59	81.21	(NEIS)	5.0 m_b	--
1986	03	30	07:42:42.1	41.37	83.67		1.4	--
1986	07	12	08:19:39.0	40.56	84.37		4.5 m_b	5-10

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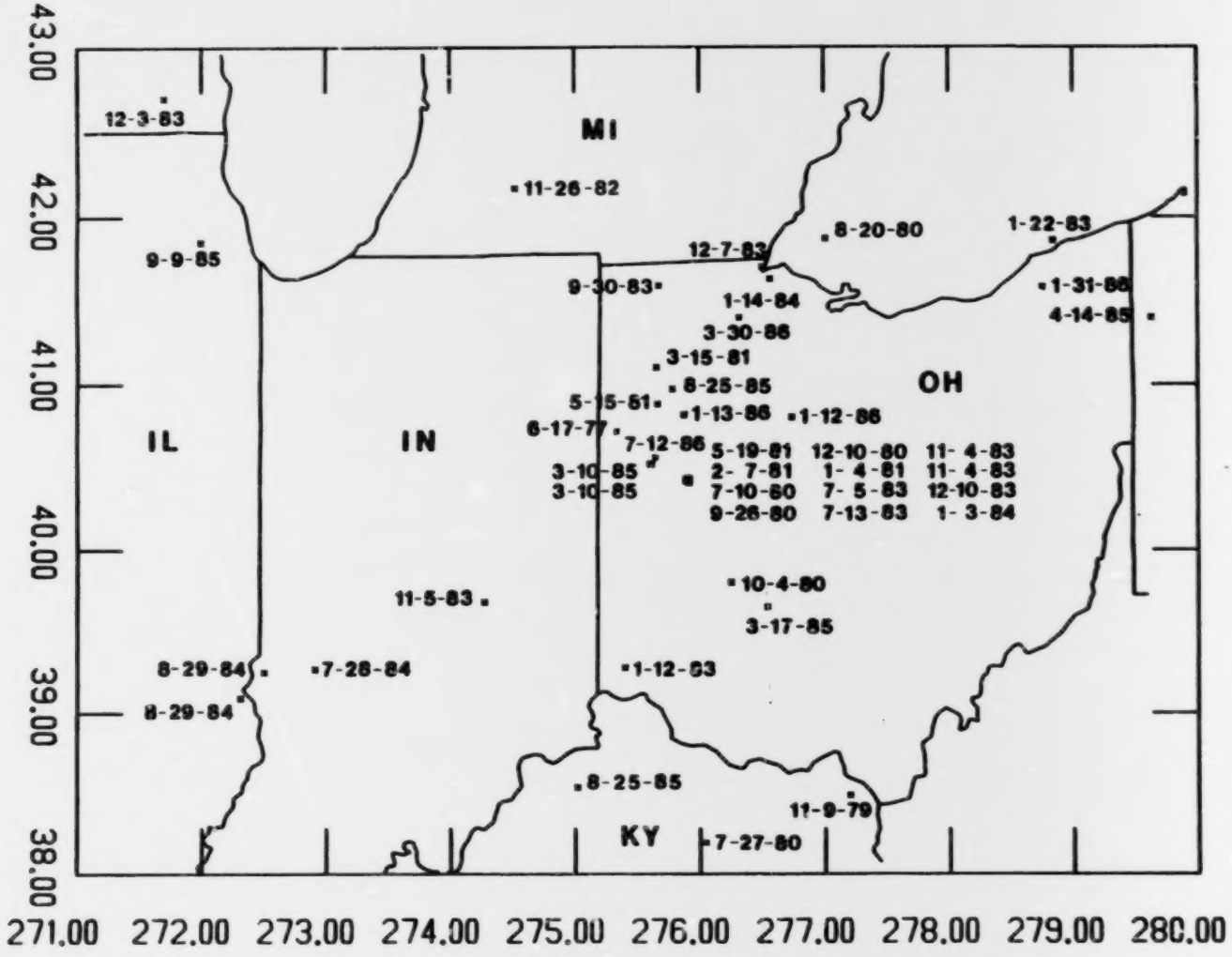


Figure 14. Local and Near-Regional Earthquake Locations from July, 1977 through September, 1986.

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TABLE 6

AVERAGE TELESEISMIC P-WAVE RESIDUALS FOR THE OHIO-INDIANA NETWORK (WITH RESPECT TO THE J-B TABLES)

Station	Average P-Wave Residual (observed minus J-B in seconds) [equal azimuthal weighting]		Number of Observations
AN1	-.60	[-.37]	278
AN3	-.56	[-.37]	274
AN4	-.57	[-.36]	271
AN7	-.56	[-.36]	255
AN8	-.54	[-.36]	222
AN9	-.53	[-.37]	272
AN10	-.63	[-.48]	276
AN11	-.74	[-.55]	307
AN12	-.55	[-.29]	294
IN1	-1.13	[-.87]	106
IN2	-.81	[-.46]	95
IN3	-.82	[-.50]	102
IN4	-1.02	[-.81]	97
ACM	-.84	[-.47]	117
AAM	-.53	[-.21]	204

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systematic biases which are not removed by averaging P-wave residuals. An example of such an effect is the systematic occurrence of many of these events in subduction zones. The P-wave residuals averaged over all arrivals at each station are plotted in Figure 15 and show essentially the same pattern as the azimuthally weighted average residuals which are not plotted. The only major difference between the two sets of residuals is a consistent difference of about .20 seconds. We can interpret the features shown in Figure 15 as following the major structural trends of the region, with the largest negative (fastest) values occurring in the center of the arch structure and the smallest negative (slowest) values occurring toward the basins (see Figure 1).

Azimuthal variations in P-wave residuals have been studied in previous reports. The following residual studies are taken from Pollack et al. (1985) using a hand-picked data set of P-wave arrival times from teleseismic events which occurred between the period June 1978 thru March 1984.

The residuals were sorted by azimuth of arrival in ten degree intervals for each of the stations and the average residual at each azimuth interval is plotted in the histograms in Figures 16a-c. The histograms for the nine Ohio stations are very similar in appearance, with relatively small positive residuals at azimuths from 30 to 140 degrees and larger negative residuals at azimuths of 150 to 330 degrees. The histograms for the Indiana stations are based on a much smaller data set and are therefore incomplete at many azimuths. Large negative residuals are the most consistent features in these histograms.

In order to remove source effects from the P-wave residuals, it is convenient to look at differences in residuals between stations instead of the absolute residual values. This effectively eliminates travel time anomalies resulting from hypocentral mislocation, structure at the source, and mantle path structure since all of the rays travel essentially the same path to the stations. This leaves only the shallow heterogeneous structure beneath the stations to account for the differences. In earlier reports we arbitrarily chose the western most Ohio station (AN11) as the standard by which to measure the residual differences. For each station, residual differences were calculated (observed residual minus AN11 observed residual). These differences were averaged over ten degree azimuth intervals for each station and are plotted in Figures 17a-c. There are several observations that can be made from these histograms. Nearly all of the values for the Ohio stations are positive and become larger toward the northeast. This means that the shallow velocity structure across the array changes from fastest in the western part of Ohio to slowest in the northeast. The residual differences for the Indiana stations are mostly negative, indicating faster than average velocities relative to the Ohio portion of the array.

It is informative to look at the residuals in greater detail. We have back projected each of the rays to a common

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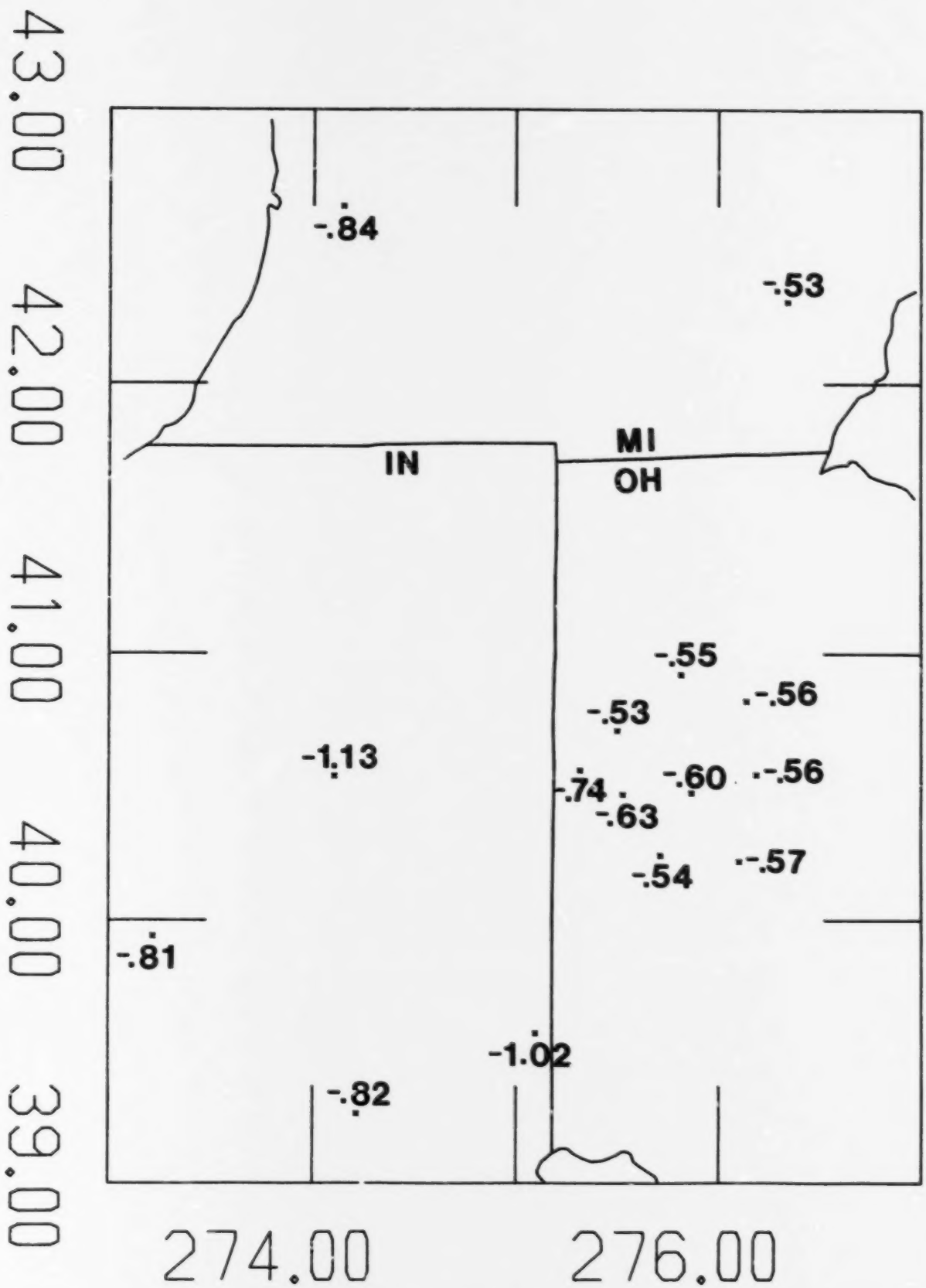


Figure 15. Map of P-Wave Residuals for the Ohio-Indiana Network (with respect to the J-B Tables). The residuals are averaged over all arrivals at each station.

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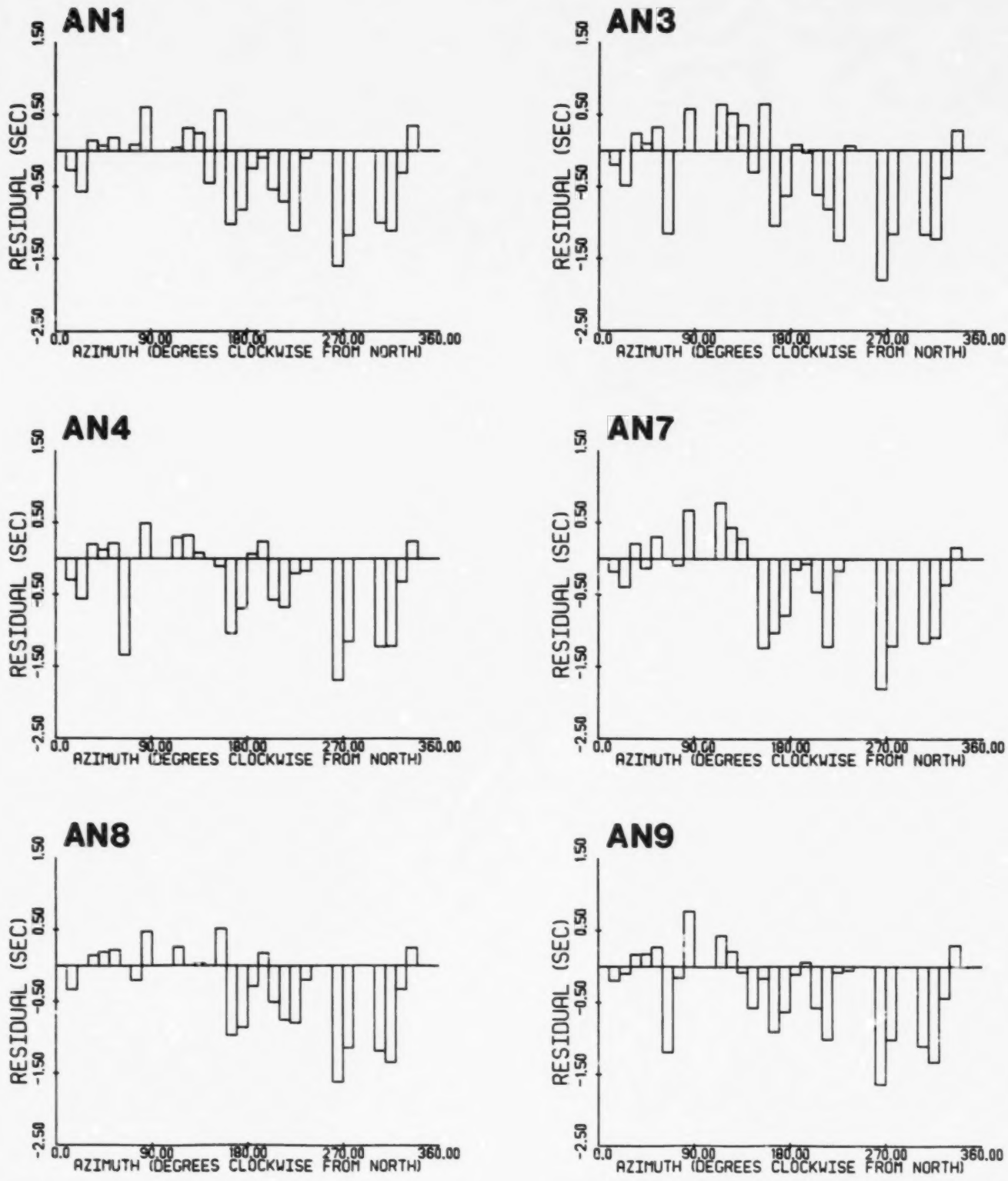


Figure 16a. Average Teleseismic P-Wave Residuals vs. Azimuth for the Ohio-Indiana Network. Stations AN1, AN3, AN4, AN7, AN8, and AN9.

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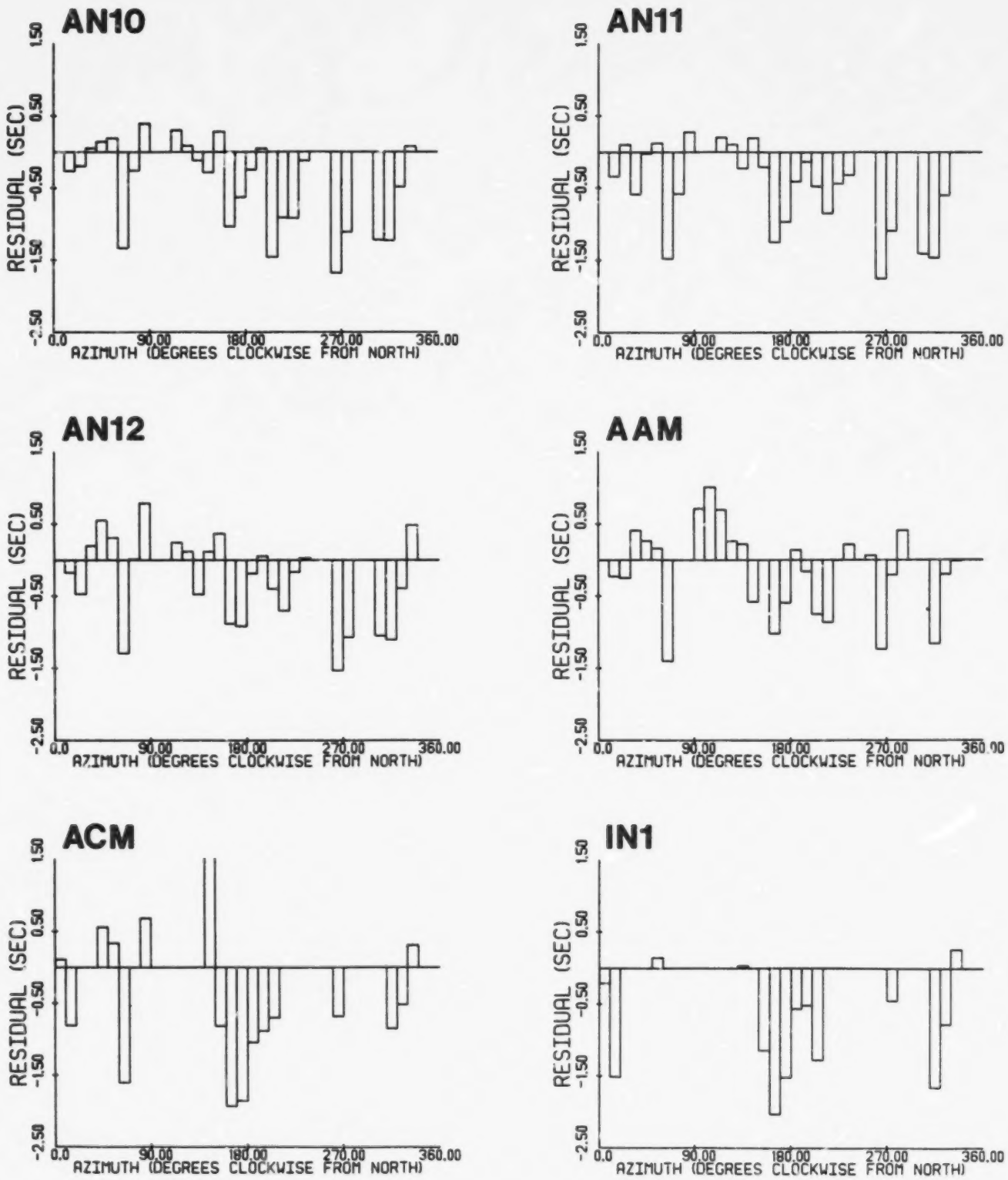


Figure 16b. Average Teleseismic P-Wave Residuals vs. Azimuth for the Ohio-Indiana Network. Stations AN10, AN11, AN12, AAM, ACM, and IN1.

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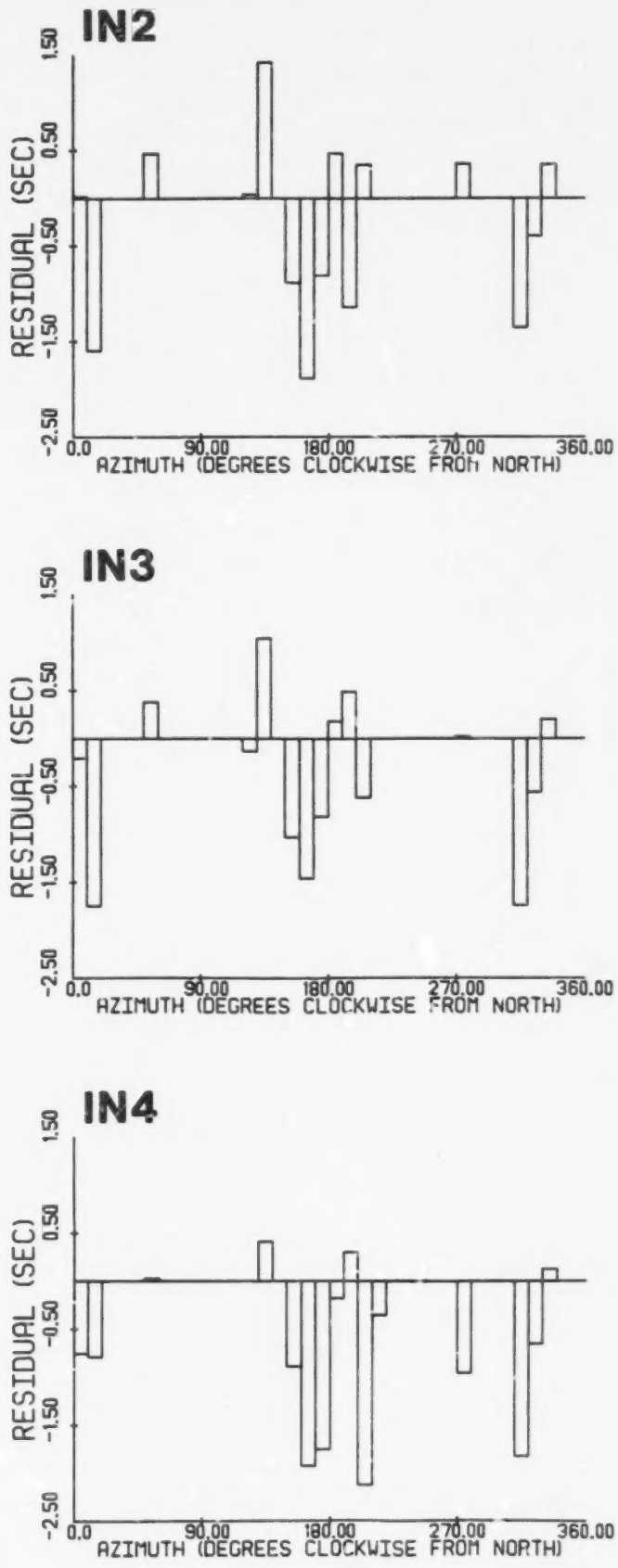


Figure 16c. Average Teleseismic P-Wave Residuals vs. Azimuth for the Ohio-Indiana Network. Stations IN2, IN3, and IN4.

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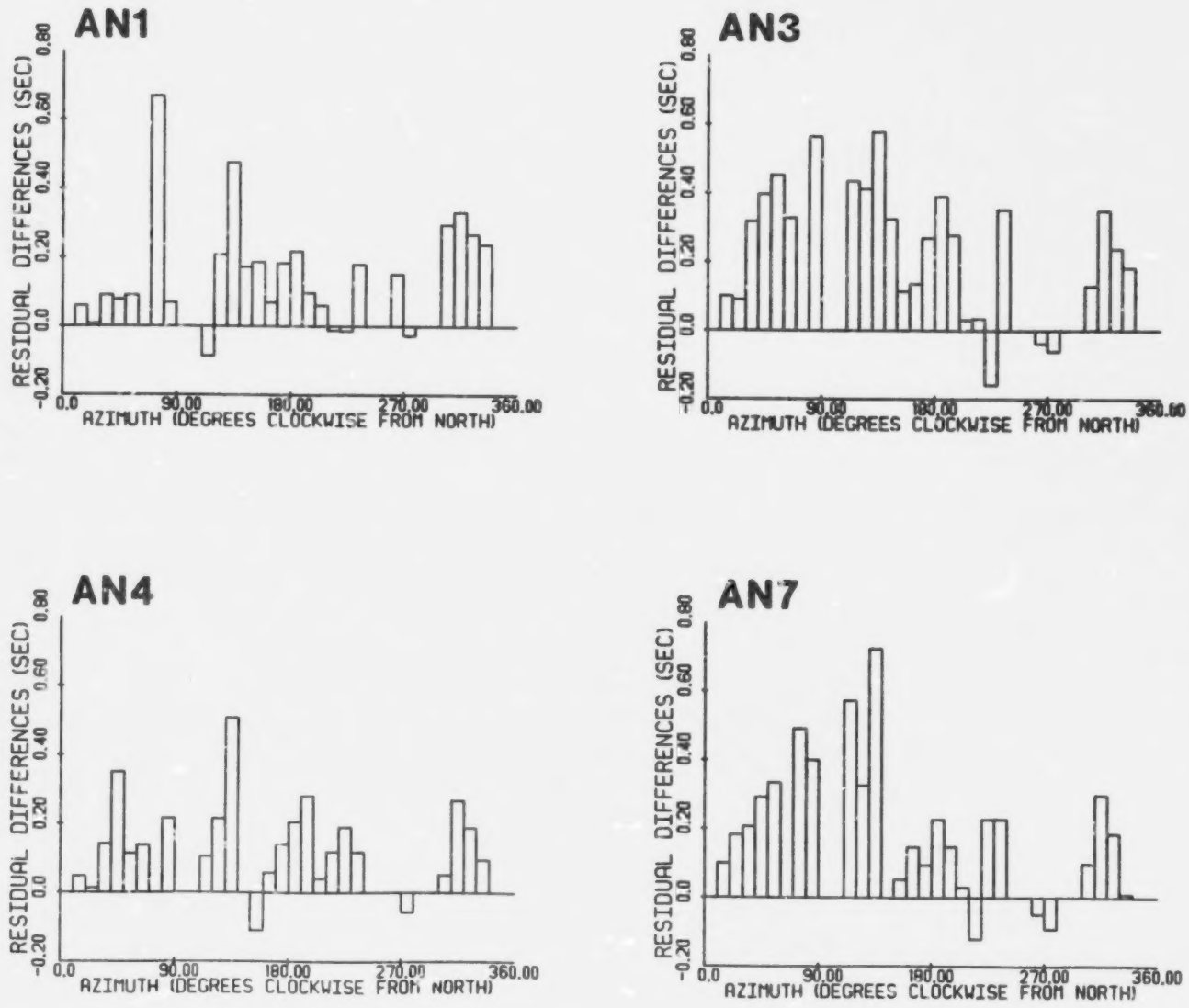


Figure 17a. Differences in P-Wave Residuals Between Stations Relative to AN11 vs. Azimuth (Station residual minus AN11 residual). Stations AN1, AN3, AN4, and AN7.

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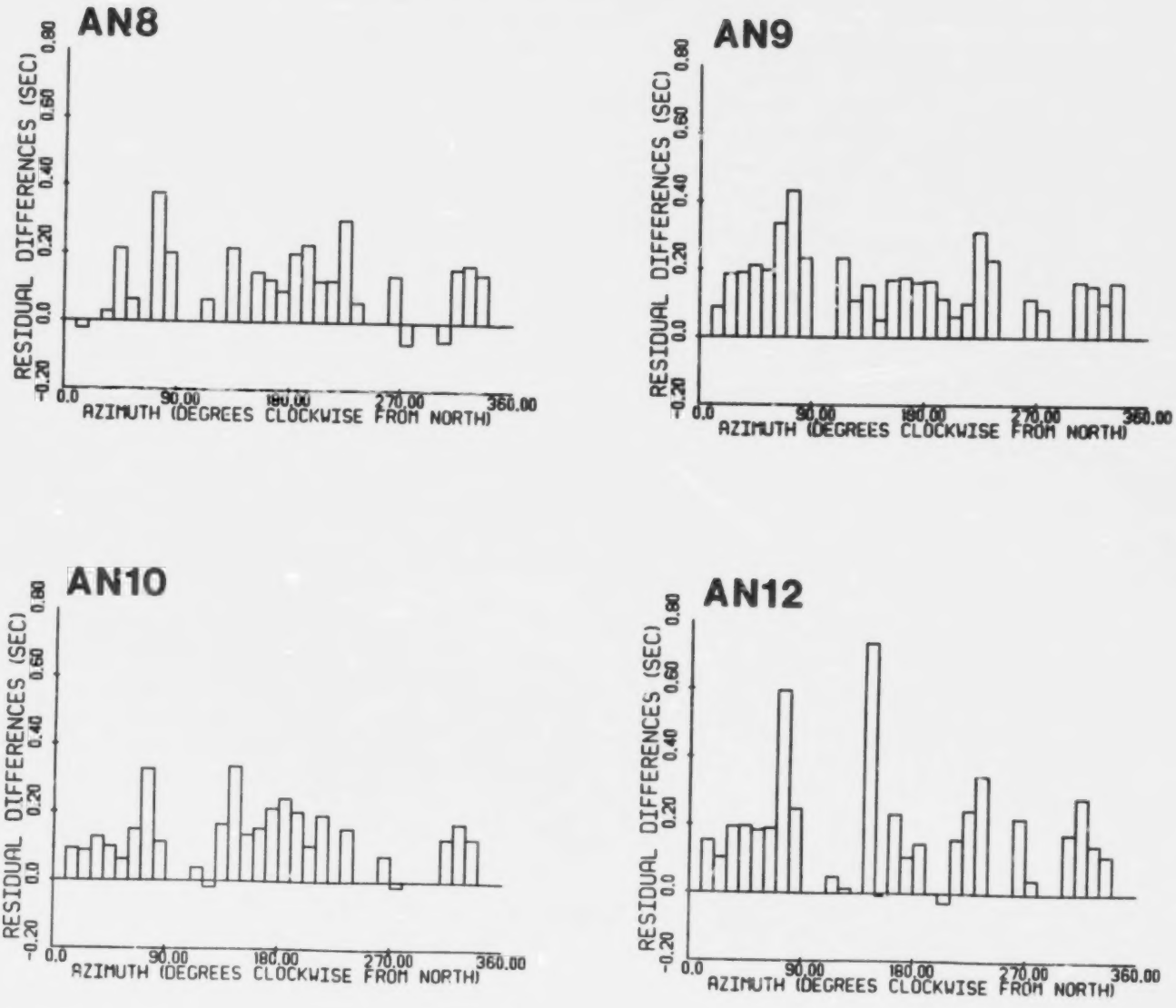


Figure 17b. Differences in P-Wave Residuals Between Stations Relative to AN11 vs. Azimuth (Station residual minus AN11 residual). Stations AN8, AN9, AN10, and AN11.

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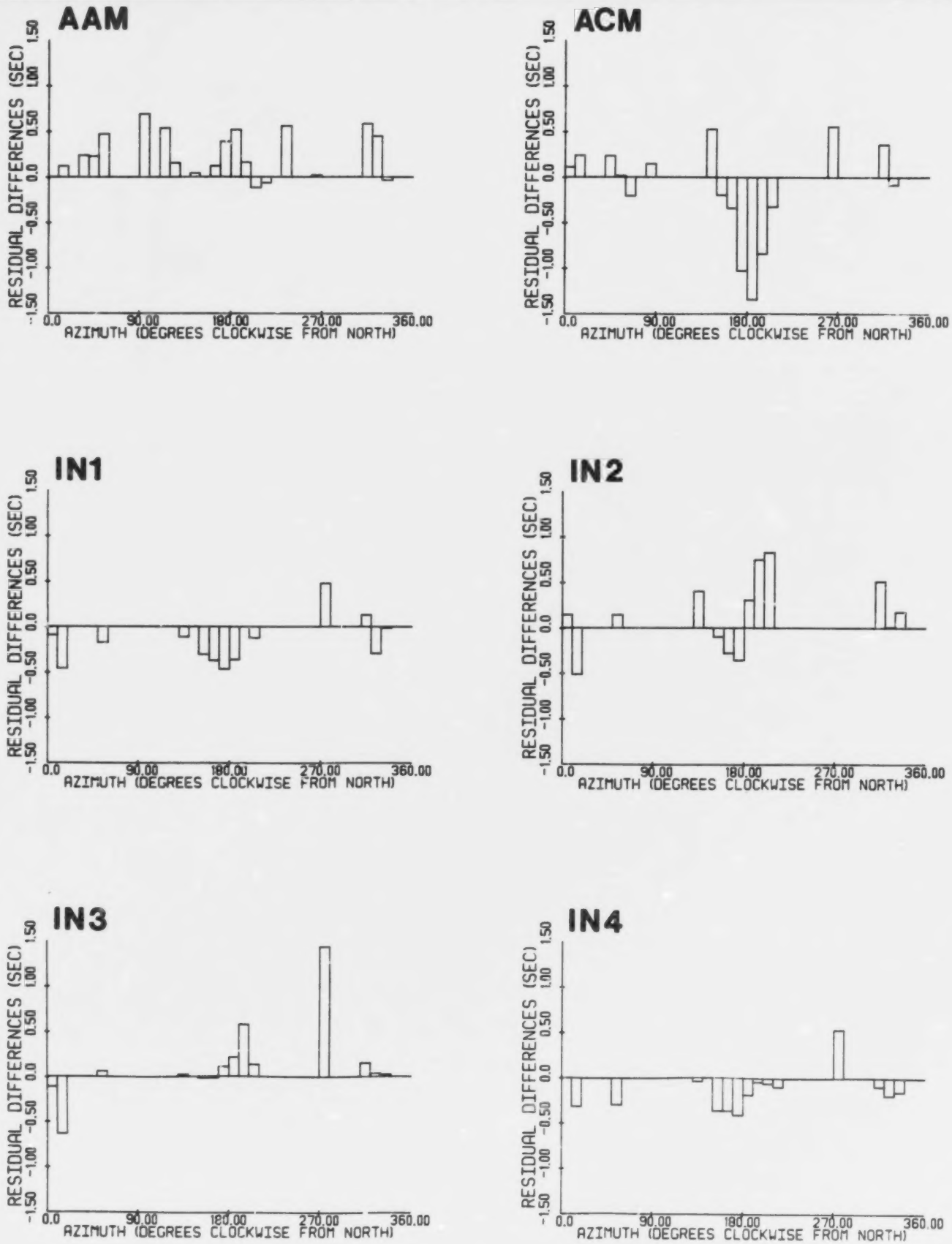


Figure 17c. Differences in P-Wave Residuals Between Stations Relative to AN11 vs. Azimuth (Station residual minus AN11 residual). Stations AAM, ACM, IN1, IN2, IN3, and IN4.

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depth using the appropriate back azimuth, angle of incidence and a simple velocity structure and plotted the residuals where each ray intersects the given depth in much the same manner as Haddon and Husebye (1978). The goal is to determine whether the patterns from the various stations will merge into a smooth, coherent pattern at a particular depth and to see if the anomalous regions can be correlated with other geophysical measurements. We will compare our results to magnetic anomaly data. A recently published aeromagnetic map (Hildenbrand and Kucks, 1984) is shown in Figure 18 along with the locations of the Ohio seismic stations for scale. The N-S trend of magnetic highs on the eastern margin of this map is part of a larger band of magnetic highs which run N-S the entire length of Ohio. This anomaly has been suggested to be the remains of an ancient rift zone or perhaps the signature of the Grenville Front which may run through the region (see Keller et al., 1982 and 1983).

In Figure 19 we have plotted the back projected relative residuals for the Ohio portion of the array (station residual minus AN11 residual) to a depth of 50 km. The number of points plotted in Figure 19 have been reduced because of the large number of rays used, by averaging the relative residuals over a five by five kilometer grid and plotting the mean value in each grid element as a single symbol. Positive residuals represent relatively late arrivals and are plotted as plus signs. Negative residuals are plotted as diamonds and represent relatively early arrivals. The size of the symbols are directly proportional to the size of the residual. Figure 19 is plotted at the same scale as the magnetic map (see Figure 18) so that the residuals can be visually compared to the magnetic anomaly map. The residuals in Figure 19 clearly show the gradual increase in residual from west to east, as well as the region of large positive residual differences in the extreme eastern part of the figure. In addition there is a good correlation between the very large positive residuals in the extreme eastern section of the array and the line of magnetic highs.

It is also interesting to look at the back projected relative residuals for the complete array. These residuals have also been calculated and averaged over a five by five kilometer grid, in this case using station AN10 as the base station, and are plotted in Figure 20. Once again the array stations have been plotted as the solid squares for orientation. The same symbol convention used in Figure 19 is used in Figure 20. The main feature of the projection at this scale is the change from positive residuals around the edge of the arch structure (in Ohio, Michigan, and western Indiana) to large negative residuals in the center of the platform (in central Indiana). This trend reflects the relatively fast velocities at the crest of the arch as compared to the slower velocities toward the adjacent basins. A more detailed discussion of the results of back

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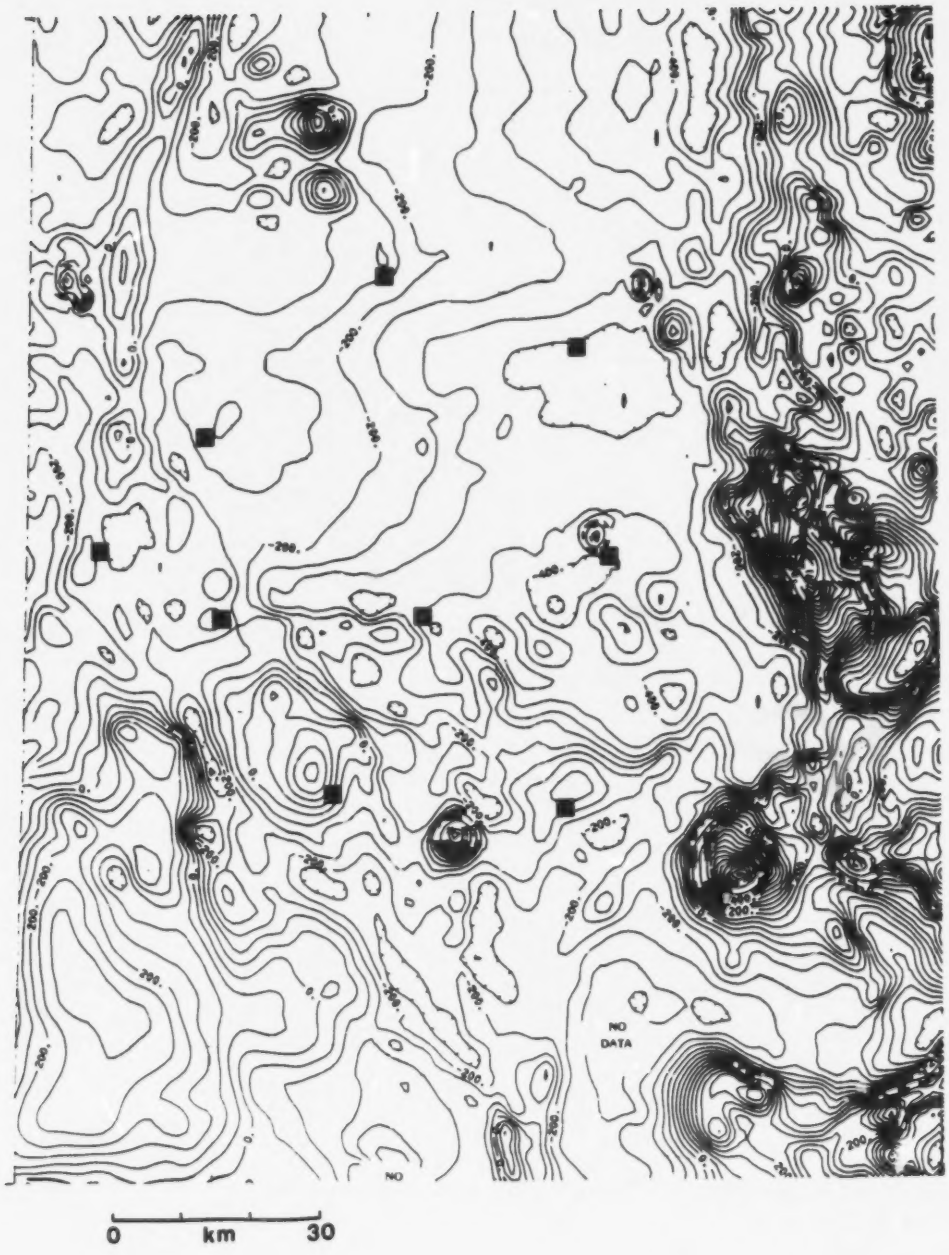


Figure 18. Aeromagnetic Map of Ohio, Residual Total Intensity Magnetic Map (from Hildenbrand and Kucks). The Ohio seismic stations are shown as solid squares. Contour interval is 50 gammas.

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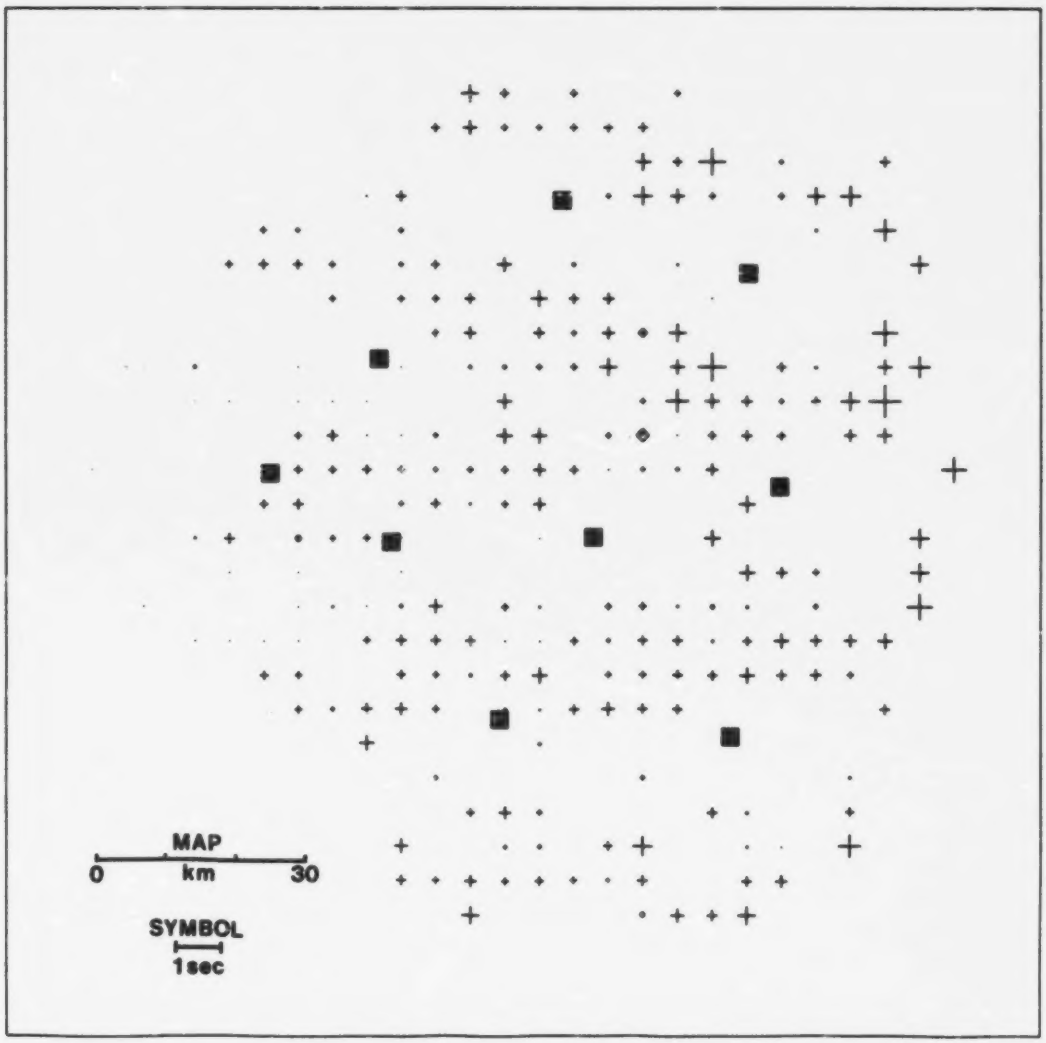


Figure 19. Back Projected Residual Differences to a Depth of 50 km for the Anna, Ohio Region. The residuals are calculated using station AN11 as the base station and are averaged over a 5 x 5 km grid. Positive residual differences are plotted as plus signs and negative residual differences are plotted as diamonds. The size of the residuals are directly proportional to the size of the symbols. Stations locations are shown as the solid squares.

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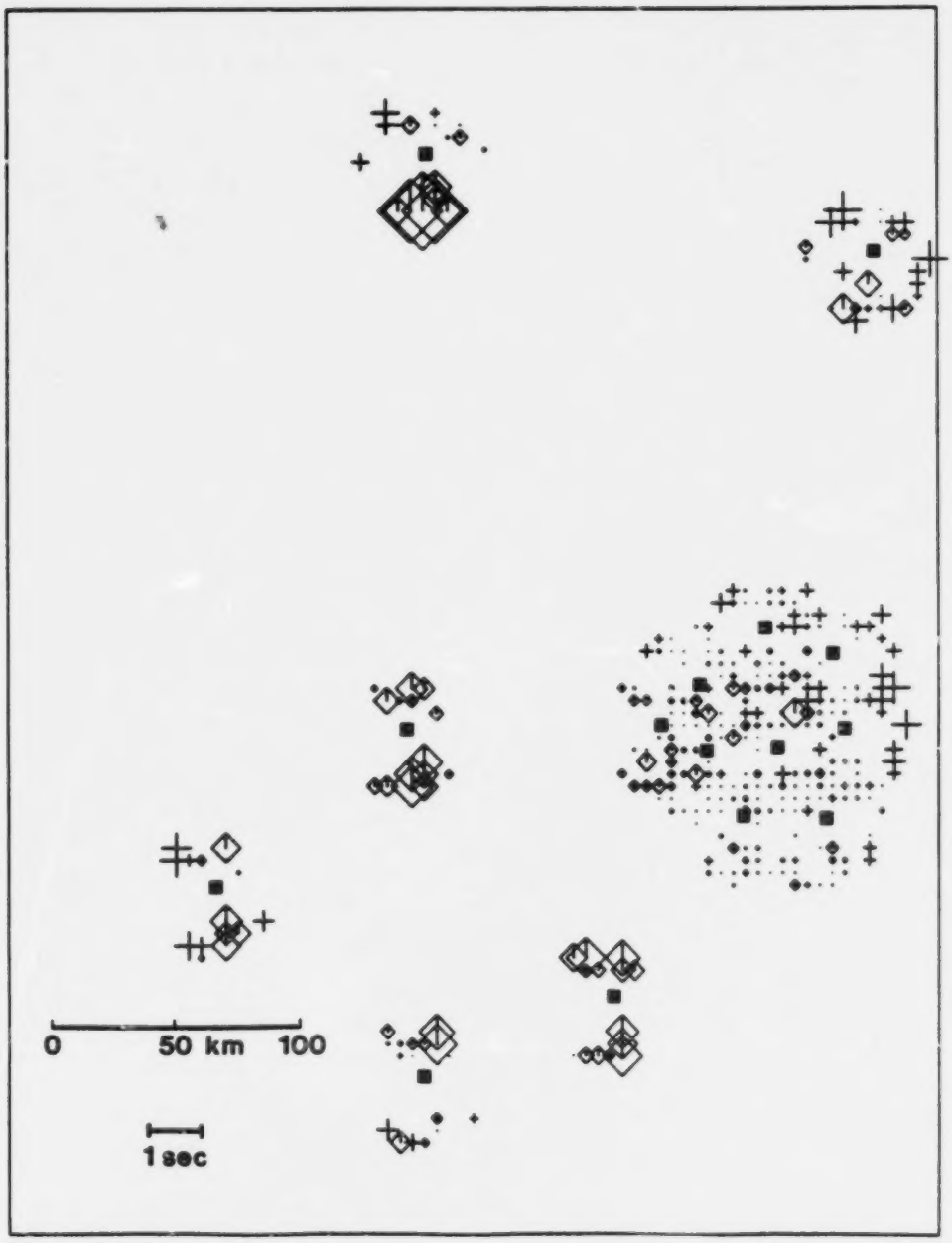


Figure 20. Back Projected Residual Differences to a Depth of 50 km for the Ohio-Indiana Network. The residuals are calculated using station AN10 as the base station and are averaged over a 5 x 5 km grid. Positive residual differences are plotted as plus signs and negative residual differences are plotted as diamonds. The size of the residuals are directly proportional to the size of the symbols. Stations locations are shown as the solid squares.

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projecting the residual differences can be found in Pollack et al. (1985).

VI
VELOCITY STRUCTURE OF THE ANNA REGION FROM TRAVEL TIME DATA

Travel Times from Local and Regional Events

Travel times for local and regional phases commonly observed on the Anna array seismograms have been compiled using phase arrival data from 64 local and regional earthquakes (epicentral distances up to 15 degrees) which occurred during June 1977 through September 1986 and phase arrival data from accurately located and timed local and regional quarry blasts. A complete listing of the earthquake parameters and phase arrival data is given in Mauk et al. (1980) for earlier events and in Table 5 and Appendix B of this report for later events. All earthquakes in this data set had reported hypocentral depths less than 25 km, and 59 of the 64 had depths reported less than 15 km. The distances covered by these data range from 5 to 1400 km. The travel time curves derived for the Anna array from the data in Mauk et al. (1980) and Appendix B are illustrated in Figure 21. In Figure 21, S-wave arrivals are shown as crosses, primary P-wave arrivals by triangles, and secondary P-wave arrivals by squares. Linear regressions of the arrival time data for subsets of the arrivals which can be identified as a particular phase yielded the best fit lines shown in Figure 22 and the associated apparent velocities listed in Table 7. The velocities listed in Table 7 are calculated from the linear regressions of arrivals in the distance range and arrival types indicated. The results suggest a fairly simple velocity model for the Anna region.

The S-wave arrival data can conveniently be separated into a direct S-wave segment (S_g or L_g) at distances less than 200 km with an apparent velocity of 3.61 km/sec and a S_n segment (S Moho) at distances greater than 350 km with a apparent velocity of 4.58 km/sec.

The P-wave arrivals are slightly more complicated with not only a direct P segment (P_g) with an apparent velocity of 6.36 km/sec and a P_n segment with an apparent velocity of 8.12 km/sec, but there are also complicated secondary P-wave arrivals at distances greater than 200 km. This secondary P-wave segment which we call P^* has been regressed in two separate segments (as shown in Figure 22) due to an obvious offset in the arrivals between the distance range 500 to 900 km (mostly from the southwest) and arrivals at distances greater than 900 km (from the northeast). The apparent velocities of 6.63 and 6.68 km/sec for these two P^* segments are very similar but offset in time (different intercept times). The offset in the two P^* arrivals may be due to the local velocity structure at the epicenters.

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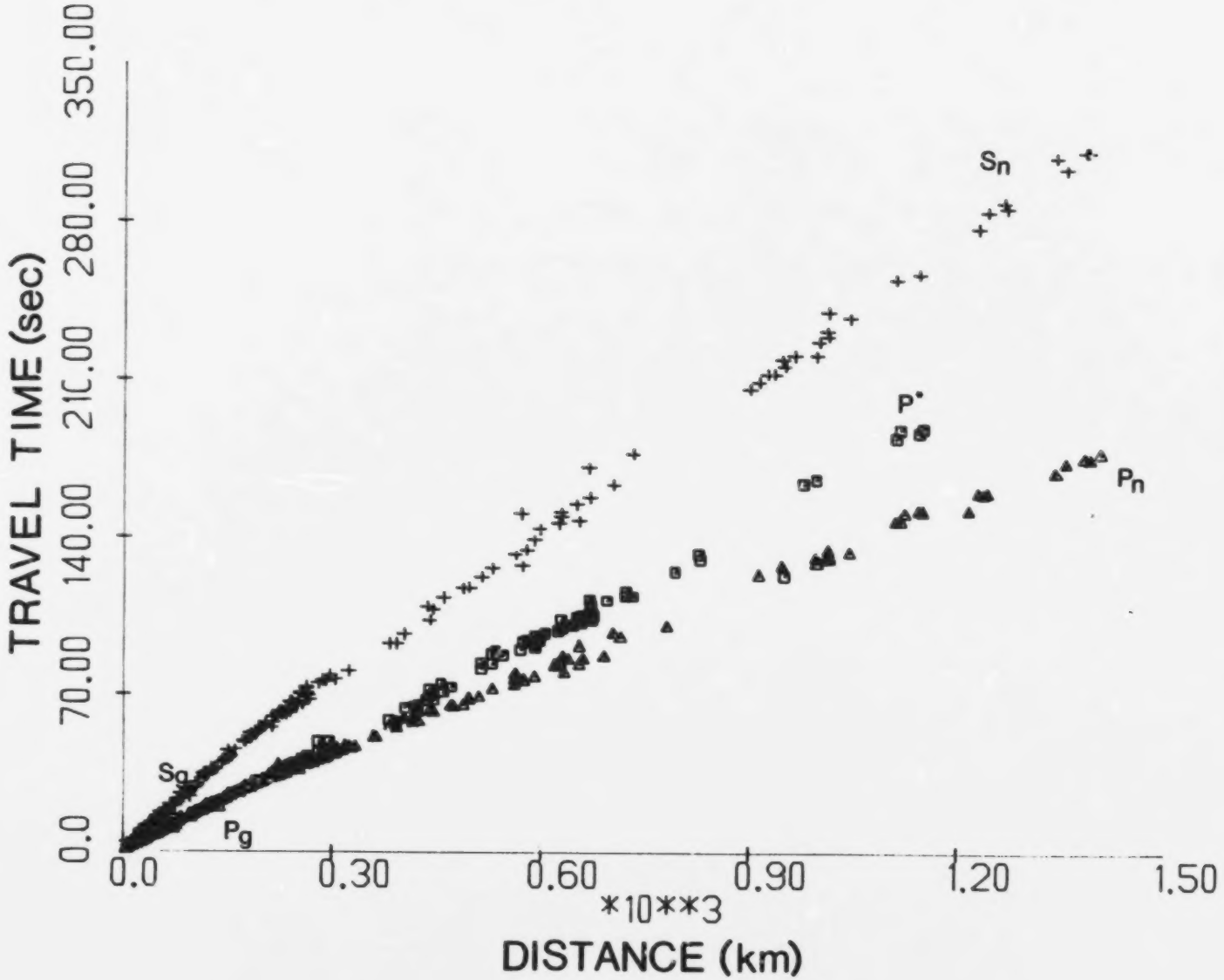


Figure 21. Travel Time Curves Derived for the Anna, Ohio, Seismic Array from Local and Regional Earthquakes and Explosions. Primary P-wave arrivals are shown as the triangles, secondary P-wave arrivals are shown as the squares, and S-wave arrivals are shown as the crosses.

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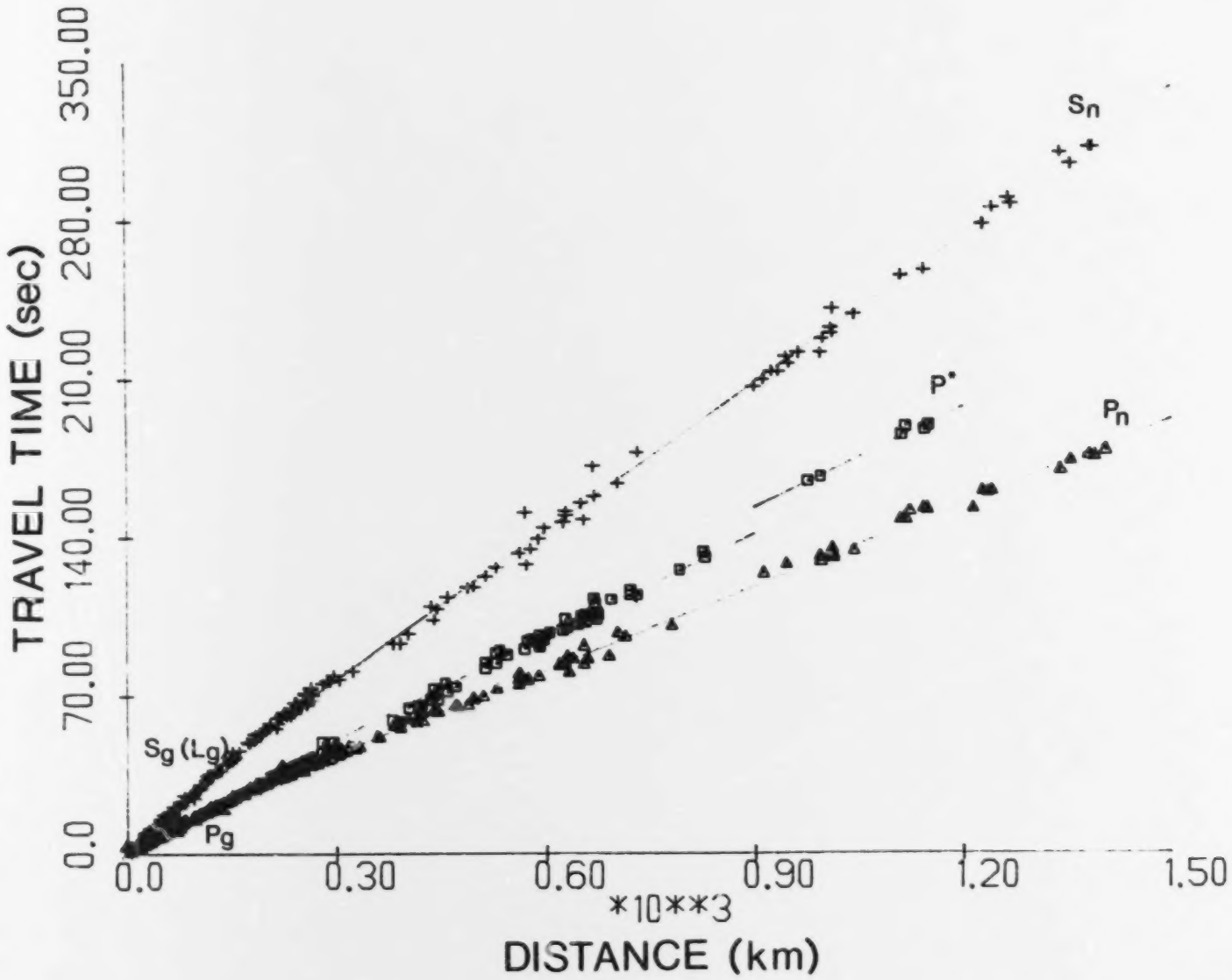


Figure 22. Travel Time Curves Derived for the Anna, Ohio, Seismic Array from Local and Regional Earthquakes and Explosions. Best-fit line segments for identifiable phases are also shown. Symbols are the same as in Figure 22.

TABLE 7

APPARENT VELOCITIES CALCULATED FROM TRAVEL TIME CURVES
(see Figure 22)

Phase	Distance Range Used in Regression (km)	Intercept Time (sec)	Apparent Velocity (km/sec)	Correlation Coefficient
P_g	0 - 200	0.63±0.06	6.36±0.03	.998
P^*	500 - 900	5.92±2.86	6.63±0.20	.984
	900 - 1500	18.18±12.99	6.68±0.54	.987
P_n	350 - 1500	7.45±0.78	8.12±0.06	.998
S_g (L_g)	0 - 200	0.80±0.17	3.61±0.03	.998
S_n	350 - 1500	11.30±1.74	4.58±0.04	.998

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The crossover distance for both the P/P_n and S/S_n systems is at about 200 km and thus the travel time curves in this distance range, between 200 and 350 km, are very complicated and hard to interpret. The depth to Moho, ≈38 km has been calculated using the intercept time of the P_n segment, and assuming an upper layer velocity of 6.36 km/sec (i.e. disregarding the complicated P^* arrivals). This depth agrees very well with other estimates of Moho depth in this region (see Braile, 1986).

Refraction Study (Summer 1984)

A joint study with the University of Kentucky and Memphis State University was undertaken in the summer of 1984. The purpose of this study was to determine the seismic velocities of the upper crust along N-S refraction profiles extending from a blast site in southeastern Kentucky, north to northwestern Ohio, and south to southeastern Tennessee. The University of Michigan was responsible for the portion of the northern line from the Ohio River to the permanent stations of the Ohio array. This section will review the data collection and the preliminary conclusions which were made from the data gathered in the northern portion of the refraction line (Pollack et al., 1986). The complete data set for the northern line has been compiled by the University of Kentucky.

The energy sources used in this study were mine blasts from a coal mine in southeastern Kentucky that regularly detonated up to 120,000 lbs. of ammonium nitrate. The location, dates and times of these blasts are listed in Table 8. The blast site was monitored by the University of Kentucky from May 1, 1984 to August 16, 1984. The majority of the blasts were timed on the basis of seismograms from a Sprengnether MEQ-800b portable seismograph situated near the blast site and corrected for offset in the instrument location from the blast site by noting the distance to the blast and assuming a sedimentary P-wave velocity of 5.55 km/sec. Origin times are believed to be accurate to about 1/80th of a second.

The locations of the temporary recording sites and distances from the blast source are listed in Table 9 and shown in Figure 23 along with the permanent stations of the western Ohio - Indiana array. There are sixteen temporary station sites with approximately 10 km spacing. These stations run from the Ohio array station AN4 to near Maysville, Kentucky and are labeled M1 through M16 from north to south (see Figure 23 and Table 9). Three Teledyne Geotech Portacorders and one Sprengnether MEQ were used to occupy the temporary station sites over the time period June 25 through August 13, 1984. During this time period 14 blasts were monitored at thirty-five locations (i.e. many stations were occupied more than once); however, in the final analysis only data from nine of the sixteen stations

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TABLE 8

BLASTING SCHEDULE DURING REFRACTION STUDY

Location: 37.417°N, 83.117°W
Southeastern Kentucky

Date Mo-Day	Time Hr-Min-Sec	Date Mo-Day	Time Hr-Min-Sec
May 01	21:38:08.580	Jun 25	22:15:03.401
May 03	22:44:23.209	Jun 27	21:05:43.313
May 19	18:00:52.509	Jun 27	21:09:38.992
May 23	21:09:17.996	Jul 02	21:05:50.529
Jun 04	21:03:19.859	Jul 09	21:08:41.492
Jun 05	21:06:12.232	Jul 17	21:03:21.125
Jun 07	21:05:42.546	Jul 27	21:08:30.325
Jun 11	21:06:59.109	Jul 31	21:22:14.510
Jun 12	21:32:09.179	Aug 02	21:02:52.475
Jun 15	21:02:43.342	Aug 06	21:49:20.740
Jun 18	21:14:42.967	Aug 08	21:07:08.288
Jun 19	21:05:39.941	Aug 10	21:00:12.088
Jun 20	21:07:52.379	Aug 13	21:15:57.608
Jun 21	21:06:56.017	Aug 16	21:04:12.942
Jun 22	21:07:57.492		

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TABLE 9

RECEIVER LOCATIONS
FOR REFRACTION SURVEY

STATION	LATITUDE °N	LONGITUDE °W	DISTANCE FROM BLAST (km)
	Temporary Stations		
M1	40.1544	83.8878	311.3
M1a	40.1529	83.8877	311.1
M2	40.0716	83.8701	302.0
M3	39.9900	83.8536	292.8
M3a	40.0166	83.8664	295.9
M4	39.8773	83.8720	281.0
M5	39.7972	83.8511	271.9
M6	39.7259	83.8322	263.8
M7	39.6317	83.8114	253.3
M8	39.5430	83.8075	243.6
M9	39.4405	83.7801	232.0
M10	39.3530	83.7757	222.5
M11	39.2652	83.7615	212.8
M12	39.1758	83.7533	203.1
M13	39.0765	83.7499	192.4
M14	38.9854	83.7365	182.4
M15	38.9057	83.7238	173.6
M16	38.8241	83.7041	164.5
	Permanent Stations		
AN1	40.4792	84.1309	351.2
AN3	40.5489	83.8121	353.0
AN4	40.2222	83.8978	318.8
AN7	40.8235	83.8602	383.7
AN8	40.2441	84.2860	329.9
AN9	40.7118	84.4967	334.9
AN10	40.4729	84.4700	359.0
AN11	40.5638	84.6804	374.8
AN12	40.9217	84.1823	399.9
IN1	40.5420	85.8940	422.2
IN2	39.9390	86.7830	424.4
IN3	39.2650	85.7850	310.6
IN4	39.5700	84.9030	285.3
ACM	42.6475	85.8517	626.0
AAM	42.2997	83.6561	544.3

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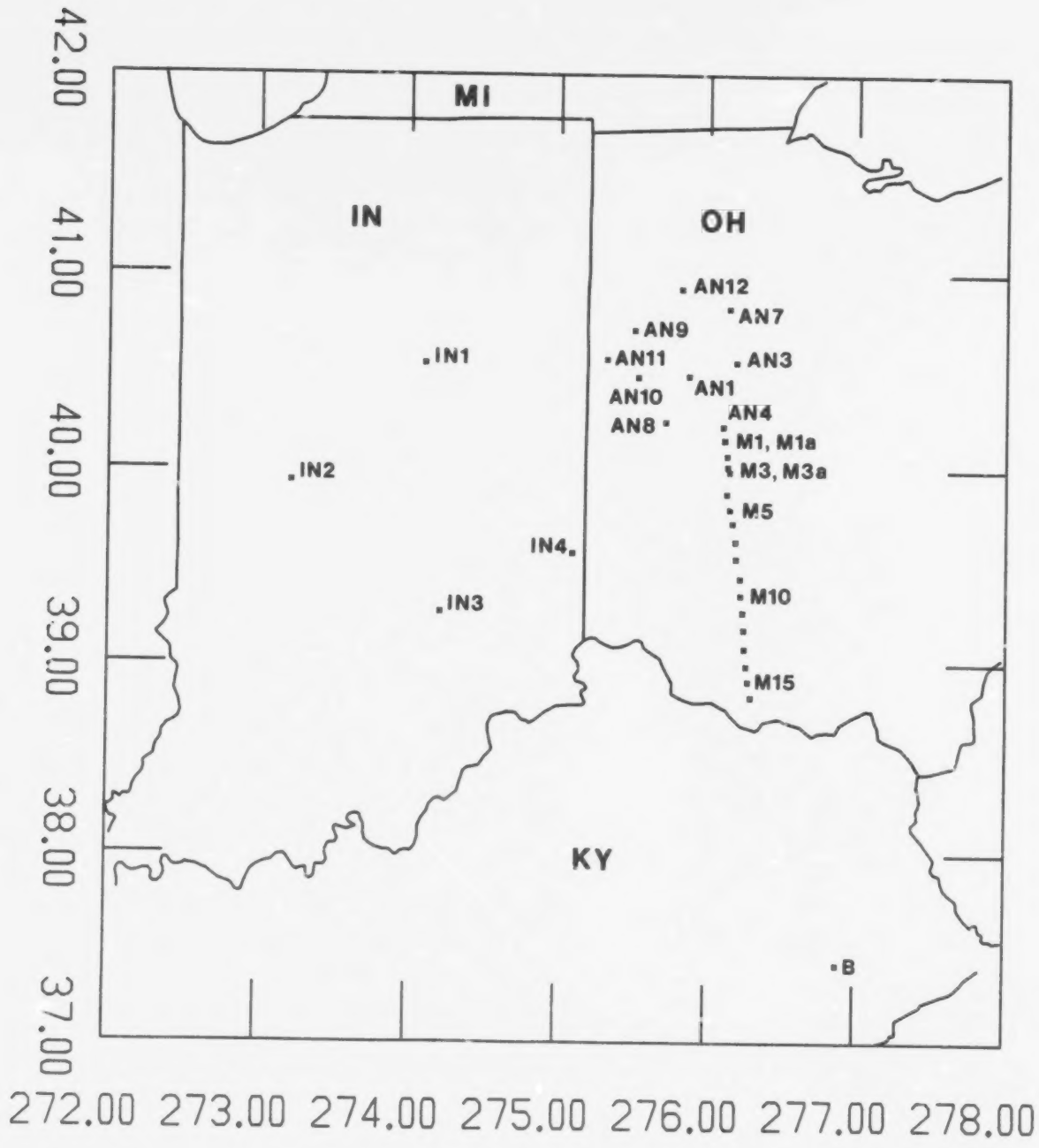


Figure 23. Locations of Temporary (M1-M16) and Permanent Seismic Stations for Refraction Profile. The point labeled B is the blast site.

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were deemed usable. One of our problems in gathering the data was the size of the blasts themselves. The temporary station sites range in distance to the blast site, from 164.5 km at station M16 to 311.3 km at station M1. During the course of the experiment we found that only the largest blasts were big enough to be recorded, particularly at the northern end of the refraction line. Since the size of a blast was not known in advance, in many cases we were not able to record the blast even though stations were installed and functional. Other problems included occasional equipment failure, and the occurrence of cultural noise during the blast arrival.

The travel time data for nine temporary sites with well recorded P-wave arrivals are listed in Table 10 and plotted in Figure 24. The points in Figure 24 fall close to a straight line which yields an apparent velocity of 6.62 km/sec; however, the data seem to suggest that the slope of the first four arrivals are slightly different from the latter five. Additional data can be used to refine these observations. The larger mine blasts were also occasionally recorded on the more distant stations of the permanent western Ohio-Indiana array. These stations range in distance from 285.3 km at station IN4 to 424.4 km at station IN2. Travel time data recorded at these stations are listed in Table 11 and plotted along with the temporary station travel time data in Figure 25. The permanent array data shows much more scatter in the observed travel times than the temporary array data, which may be due to the differences in the back-azimuth from the array stations to the blast (i.e. differences in the paths travelled). The distances to the array stations which are beyond the crossover point of P_n may also be an important factor in the data scatter. Thus at some distances P_n may be recorded first, whereas in others the refracted P-wave from the basement layers will be the first recorded arrival. Interference between these two arrivals may also cause problems in picking the arrival times. A possible interpretation of the travel time data is shown in Figure 26. The P_n travel time branch is represented by the circles and yields an apparent velocity of 8.27 km/sec and the refracted P (P_g or P^*?) travel time branch is represented by the squares and yields an apparent velocity of 6.76 km/sec. The same interpreted data is shown along with the uninterpreted University of Kentucky data in Figure 27.

Arrival times for the L_g phase were also picked and proved to be a very consistent phase. The L_g travel time data is listed in Table 12 and plotted in Figure 28 with an apparent velocity of 3.57 km/sec.

Summary of Velocity Structure Study

The results from the 1984 refraction survey tend to support the velocities found from local and regional earthquakes. The resulting velocity structure from this

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TABLE 10

TRAVEL TIME DATA FROM REFRACTION SURVEY
NORTHERN KENTUCKY - SOUTHWESTERN OHIO PROFILE

Temporary Stations

Station	Travel Time (sec)	Distance (km)
M4	43.98	281.0
M5	42.88	271.9
M6	41.65	263.8
M7	40.29	253.3
M9	37.61	232.0
M11	33.74	212.8
M12	32.26	203.1
M14	29.22	182.4
M15	28.17	173.6

TABLE 11

TRAVEL TIME DATA FROM REFRACTION SURVEY
NORTHERN KENTUCKY - SOUTHWESTERN OHIO PROFILE

Permanent Stations

Station	Travel Time (sec)	Distance (km)
AN1	52.09	351.2
AN3	54.19	353.0
AN4	49.39	318.8
AN4	49.71	318.8
AN4	49.79	318.8
AN4	50.06	318.8
AN7	59.00	383.7
AN7	55.29	383.7
AN11	54.79	374.8
AN12	58.99	399.9
IN3	50.96	310.6
IN4	43.62	285.3
IN4	44.09	285.3
IN4	44.11	285.3
IN4	44.49	285.3
IN4	44.41	285.3
IN4	44.53	285.3

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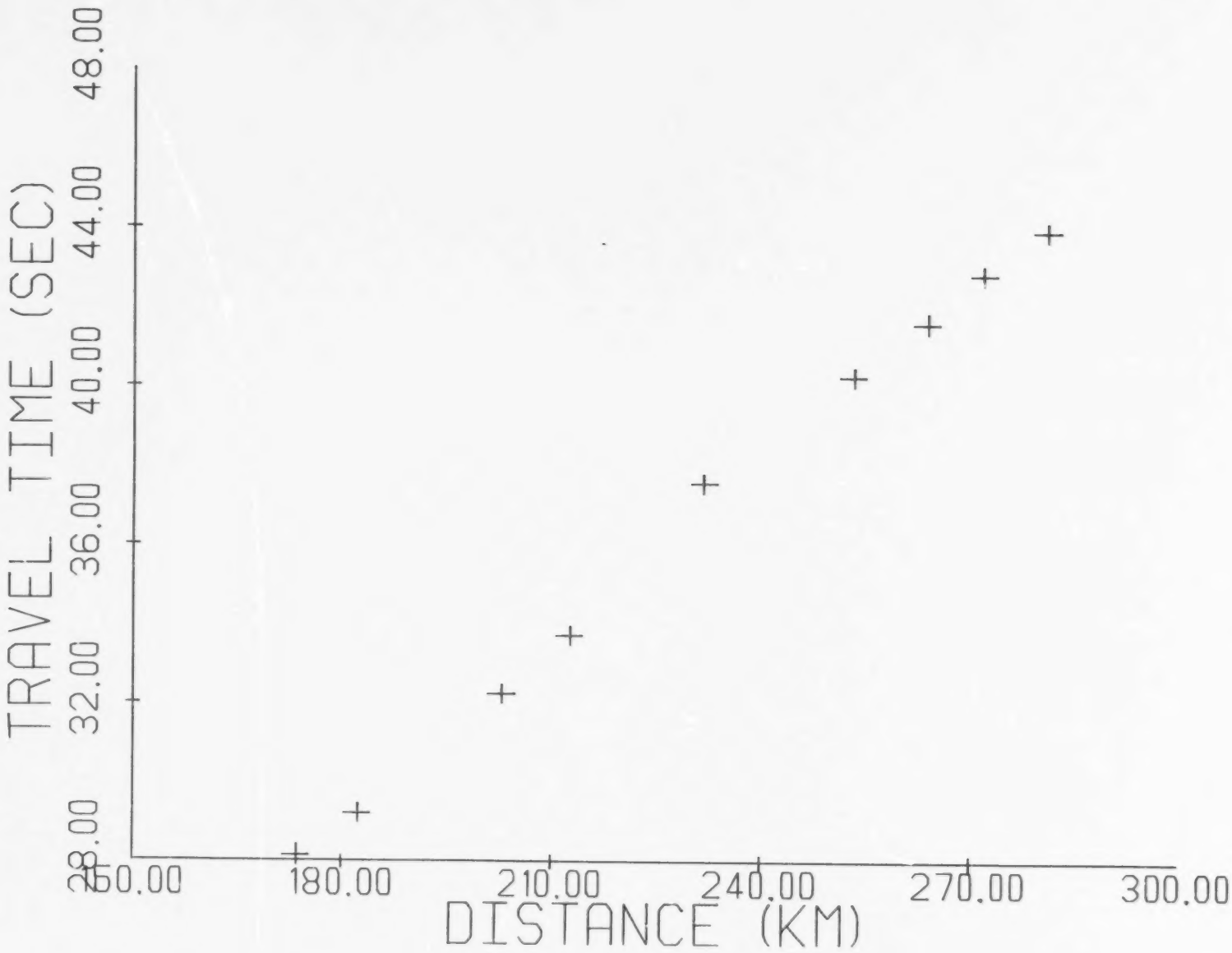


Figure 24. Travel Time Plot for Temporary Stations. Data is found in Table 10.

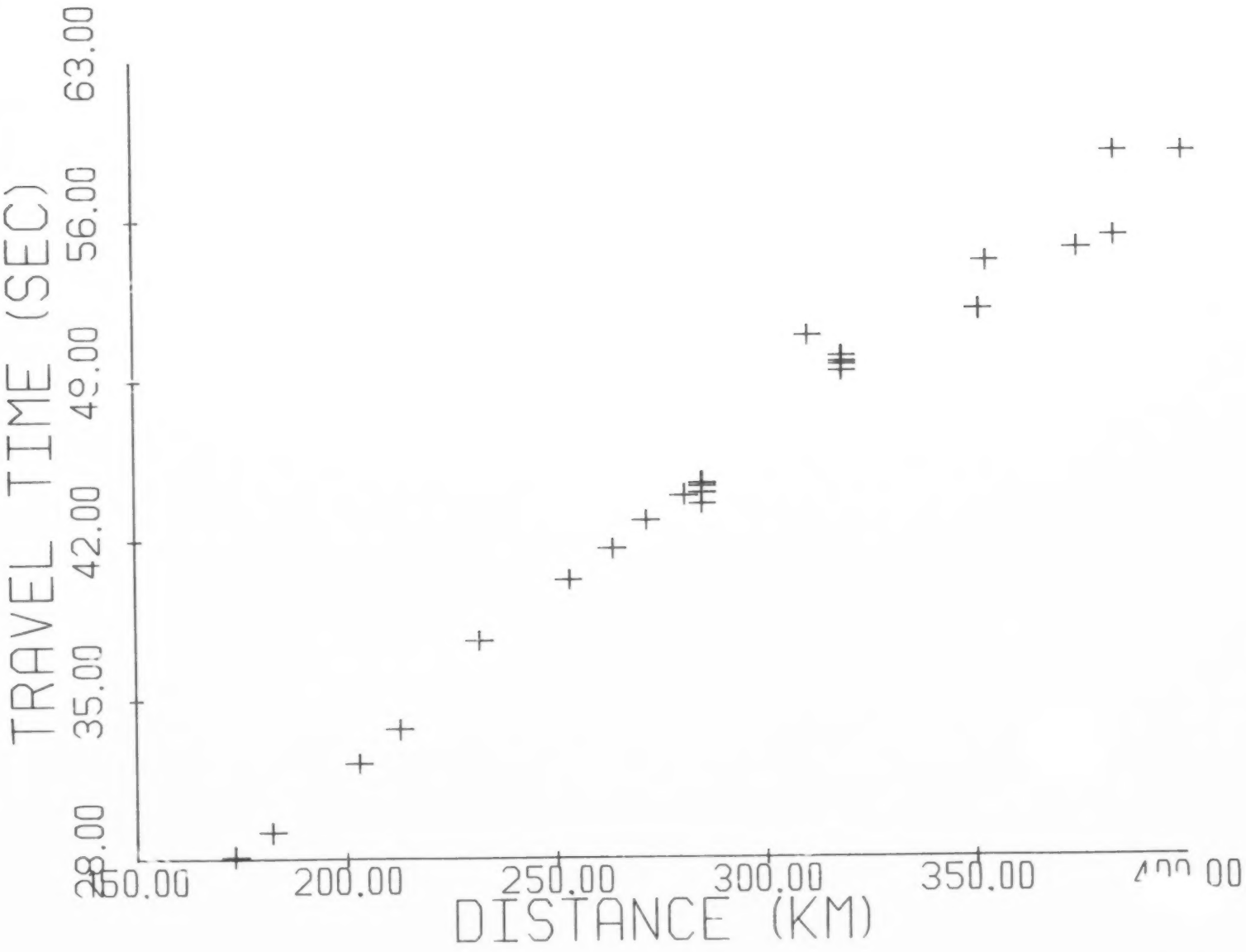


Figure 25. Travel Time Plot for Temporary and Permanent Stations. Data is found in Table 10 and 11.

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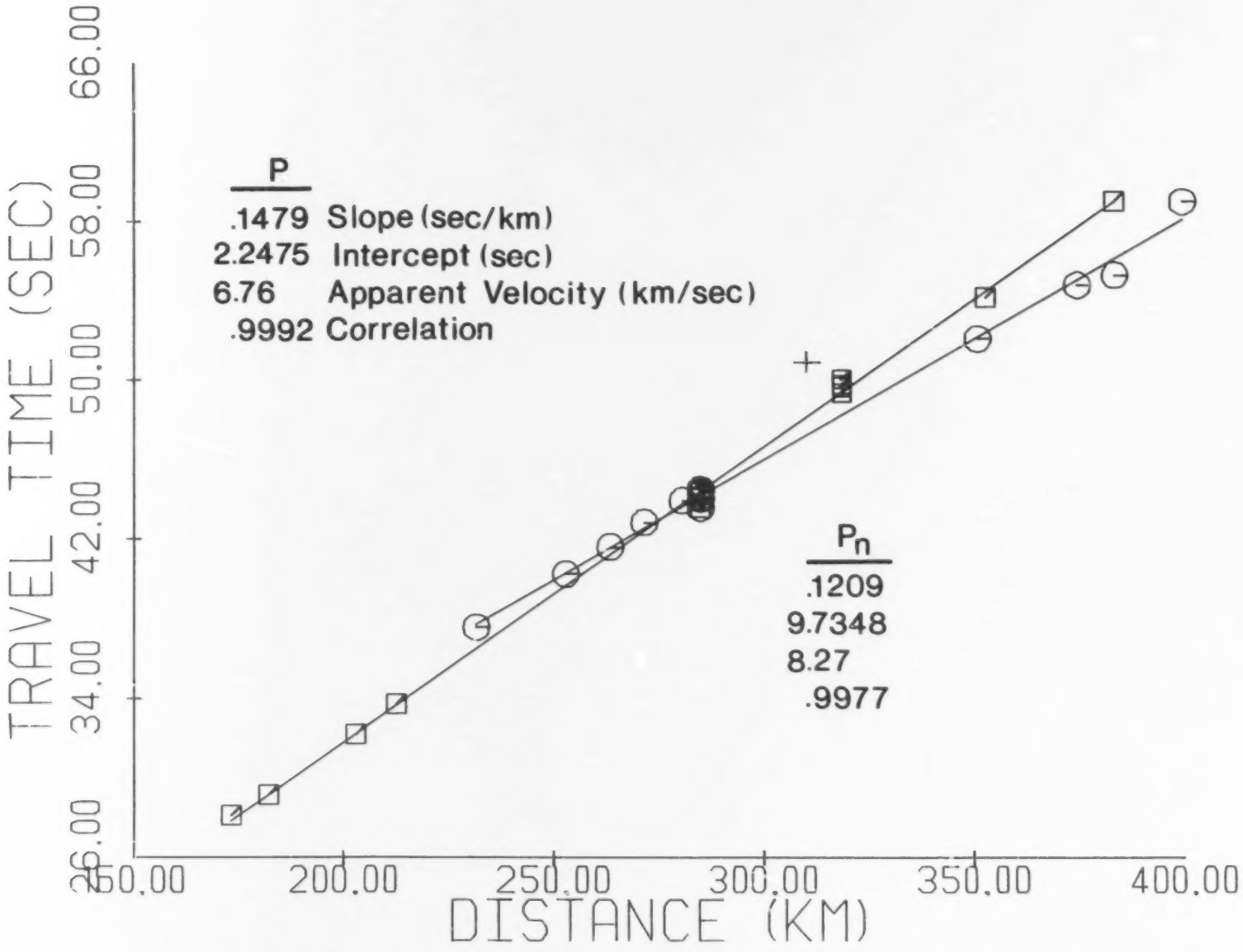


Figure 26. Interpretation of Travel Time Plot for Temporary and Permanent Stations. Apparent velocities and statistics for the best fit line of each segment of the curve are shown in the figure.

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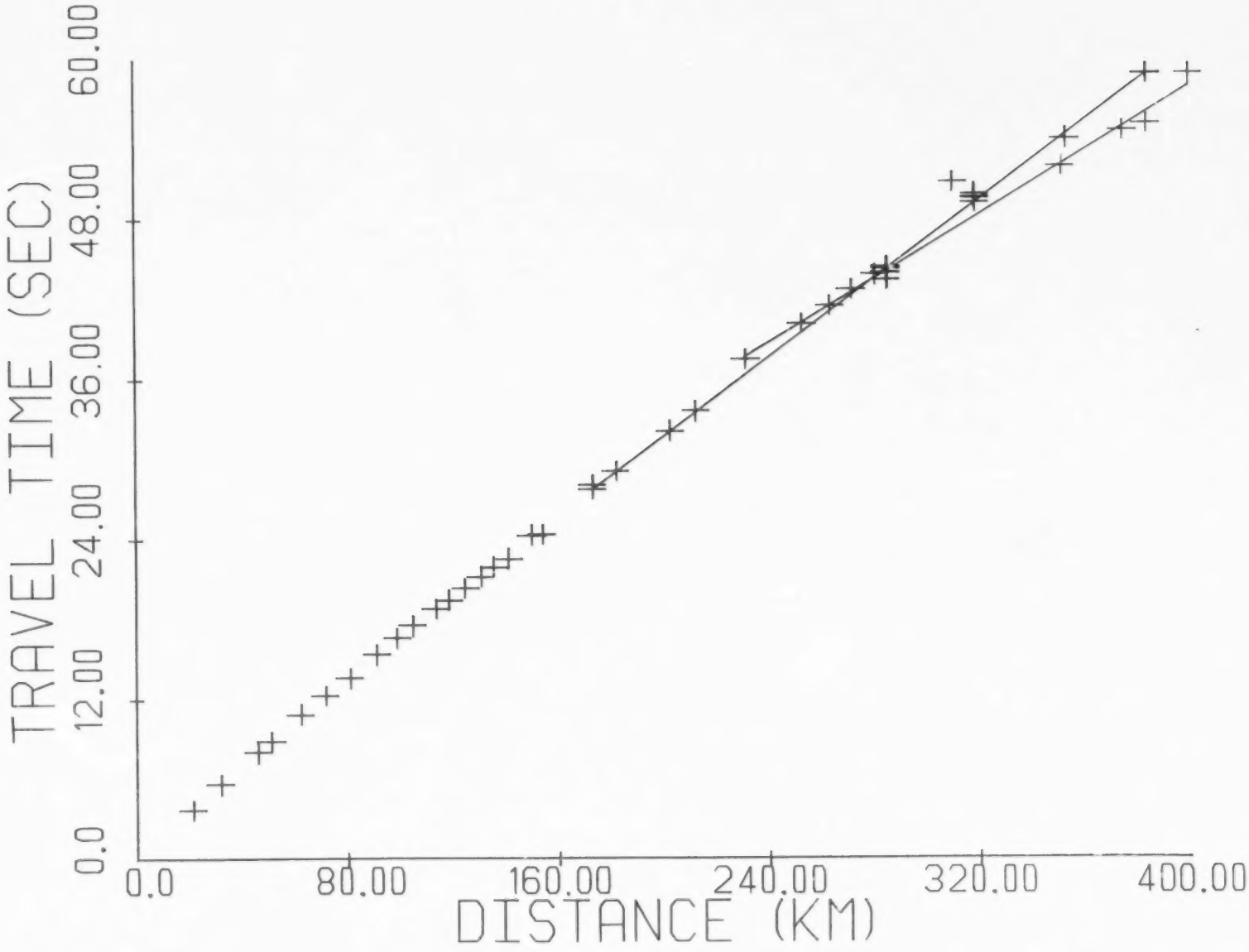


Figure 27. Travel Time Plot of Data Collected by the University of Michigan and the University of Kentucky. Line segments shown are the same as those in Figure 26.

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TABLE 12

L_g TRAVEL TIME DATA FROM REFRACTION SURVEY
NORTHERN KENTUCKY - SOUTHWESTERN OHIO PROFILE

Station	Travel Time (sec)	Distance (km)
AN3	98.69	353.0
M2	84.19	302.0
M4	78.63	281.0
M4	79.63	281.0
M5	75.53	271.9
M6	73.03	263.8
M7	70.49	253.3
M9	65.21	232.0
M10	62.09	222.5
M11	58.99	212.8
M12	56.98	203.1
M14	50.87	182.4

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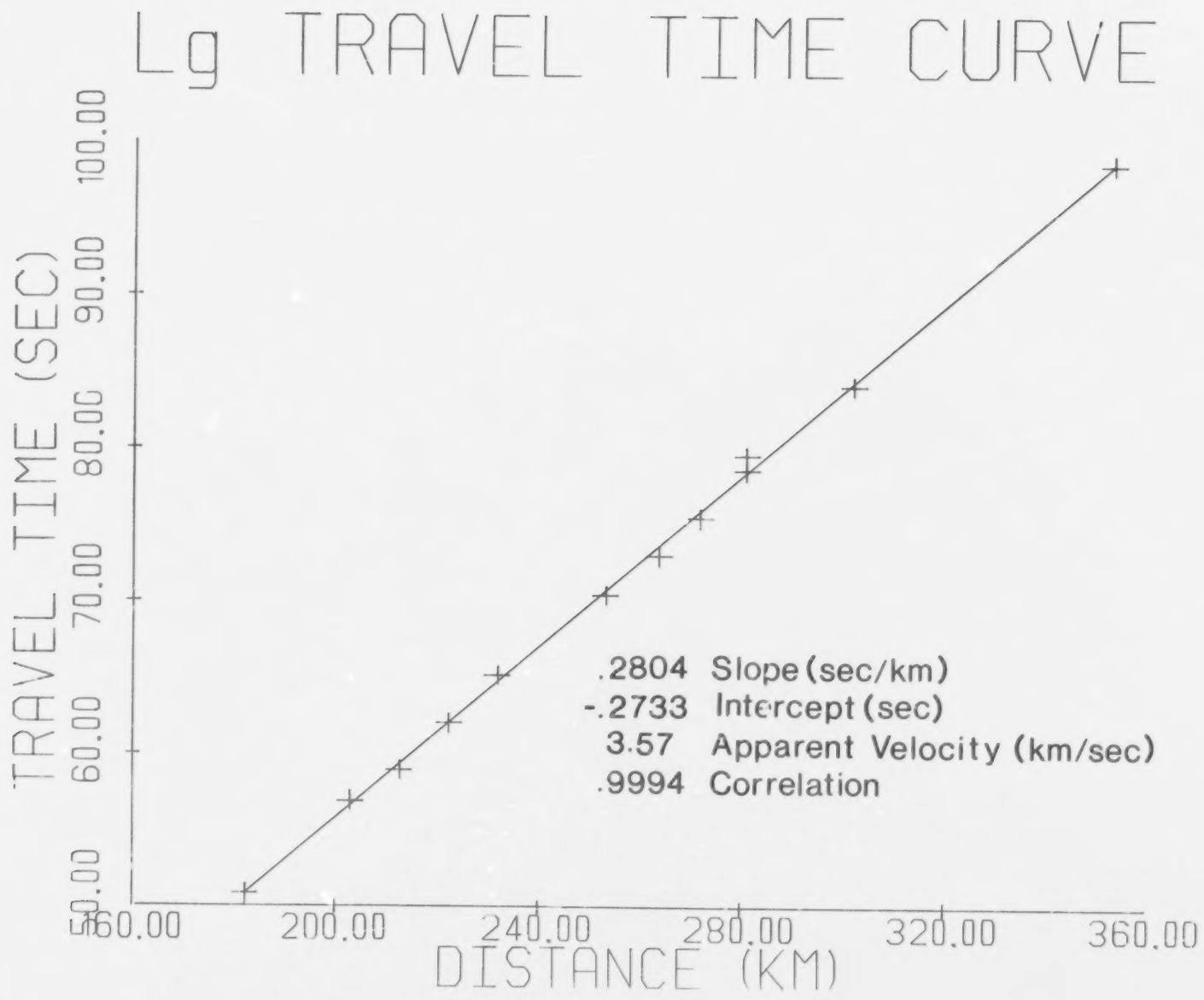
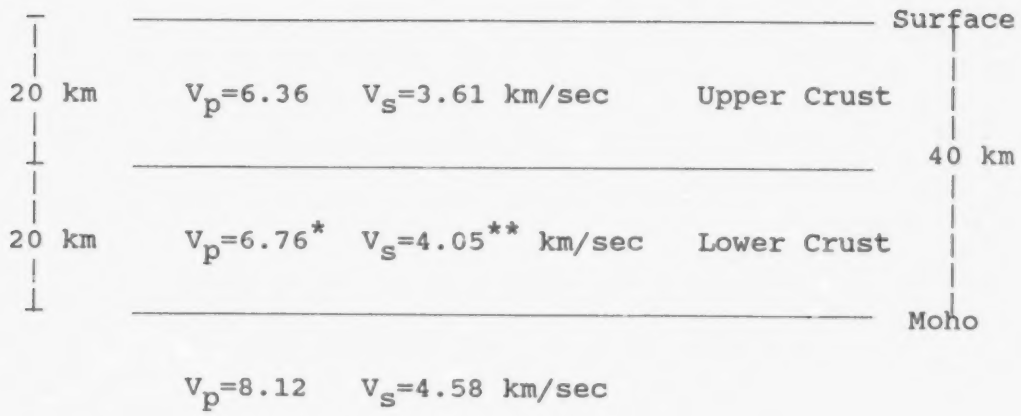


Figure 28. Travel Time Plot of L_g Arrivals. The best fit line and related statistics are shown in the figure.

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study is shown in Figure 29. This model contains two layers above the Moho; an upper crustal layer which is 20 km thick and has P- and S-wave (L_g) velocities of 6.36 and 3.57 km/sec, respectively, and a lower crustal layer (based on the 1984 refraction data) which is also 20 km thick and has a P-wave velocity of 6.76 km/sec. Although no S-wave arrivals can be interpreted for the lower crustal layer, we are able to obtain a plausible S-wave velocity of 4.05 km/sec using the P- to S-wave ratio in the upper crust. Velocities below the Moho are 8.12 and 4.58 km/sec for P_n and S_n, respectively. The P^* segments of the travel time curve in Figure 22 cannot be easily integrated with our preferred velocity structure because of their rather large intercept times; however, the apparent velocities from these segments as listed in Table 7 are consistent with the velocity in the lower crustal layer of our model.

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* Velocity from Refraction Survey
** Velocity inferred from V_p/V_s ratio

Figure 29. Velocity Structure Determined for the Anna, Ohio Region from Travel Time Study.

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13 ABSTRACT (200 words or less)

Earthquake activity in the Western Ohio - Indiana region was monitored with a precision seismograph network consisting of nine stations located in west-central Ohio and four stations located in Indiana. Five local and near-regional earthquakes were recorded during the fiscal 1985-86 report period, ranging in magnitude from 0.5 to 5.0m_b. The two largest events (January 31, 1986 near Cleveland, Ohio, 5.0m_b; and July 12, 1986 near St. Marys, Ohio, 4.5m_b) were felt with minor damage reported in each case. Focal mechanisms and isoseismal maps for these events are included in this report. These events are the largest to have occurred in Ohio since the events of March 2 and March 9, 1937 (magnitude = 4.5 and 4.9, respectively). The remaining three earthquakes all occurred in Ohio, north of the array. A total of 42 local and near-regional events, eleven of which were felt, have now been recorded by the Ohio-Indiana array since its initiation in 1976.

Teleseismic P-wave arrival and residual tables were updated to include newly acquired data. The results are similar to those in previous years. The local velocity structure was investigated using data acquired during a refraction experiment in the summer of 1984, and travel times of local and near-regional earthquakes.

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